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DISCUSSION PAPER SERIES

IZA DP No. 16396

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ABSTRACT

The Effects of Climate Change in the Poorest Countries: Evidence from the Permanent Shrinking of Lake Chad*

Empirical studies of the economic effects of climate change (CC) largely rely on climate anomalies for causal identification purposes. Slow and permanent changes in climate-driven geographical conditions, i.e. CC as defined by the IPCC (2013), have been studied relatively less, especially in Africa which remains the most vulnerable continent to CC. We focus on Lake Chad, which used to be the 11th-largest lake in the world. This African lake the size of El Salvador, Israel, or Massachusetts slowly shrunk by 90% for exogenous reasons between 1963 and 1990. While water supply decreased, land supply increased, generating a priori ambiguous effects. These effects make the increasing global disappearance of lakes a critical trend to study. For Cameroon, Chad, Nigeria, and Niger – 25% of sub-Saharan Africa's population –, we construct a novel data set tracking population patterns at a fine spatial level from the 1940s to the 2010s. Difference-in-differences show much slower growth in the proximity of the lake, but only after the lake started shrinking. These effects persist two decades after the lake stopped shrinking, implying limited adaptation. Additionally, the negative water supply effects on fishing, farming, and herding outweighed the growth in land supply and other positive effects. A quantitative spatial model used to rationalize these results and estimate aggregate welfare losses taking into account adaptation shows overall losses of about 6%. The model also allows us to study the aggregate and spatial effects of policies related to migration, land use, trade, roads, and cities.

JEL Classification: Q54, Q56, Q15, Q20, R11, R12, O13, O44

Keywords: climate change, aridification, shrinkage of lakes, natural disasters, environment, water supply, land supply, rural decline, agricultural sectors, adaptation, land use, Africa

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According to the IPCC, “climate change refers to a change in the state of the climate that can be identified [...] by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer” (IPCC, 2013). In addition, “since the late 1950s, many of the observed changes are unprecedented [...]”

Empirical studies of the causal effects of climate change [henceforth, CC] typically rely on climate anomalies for their analyses. While such studies have improved our understanding of the reduced-form effects of CC, they do not examine “changes in the mean” over several “decades or longer.” Additionally, the negative effects of climate variations should compound over time the longer they last. However, since CC is unfolding gradually, agents can also engage in a wider set of adaptations.

Theoretical studies tend to simulate the effects of future CC. While such studies have deepened our understanding of the mechanisms by which CC may have aggregate and spatial effects in the future, they are predictive exercises. As such, they do not aim to study the empirical effects of the CC that has been occurring since the late 1950s.

To investigate the effects of past CC and shed light on the possible effects of future CC, one ideally needs: (i) A permanent change in climate-driven geographical conditions; (ii) The change must take place over several decades; (iii) The change must be exogenous; (iv) Localized data must be available before, during, and after the change. However, historical data is typically lacking in the poorest countries that will be most affected by future CC, like in Africa; (v) A model that helps us rationalize the economic and spatial effects; and (vi) The model must generate clear policy prescriptions.

We combine plausibly causal empirical evidence and theory to study, over a 70-year period, the economic effects of the almost complete disappearance of Lake Chad, historically the 11th largest lake in the world. Lake Chad lost 90% of its surface water area – 23,000 sq km – between 1963 and 1990 (see Figure 1 below). This is equivalent to the total area of El Salvador, Israel plus the West Bank and Gaza, or Massachusetts. As water supply decreased and land supply increased, it generated a priori *ambiguous* local and aggregate economic effects, which must be investigated.

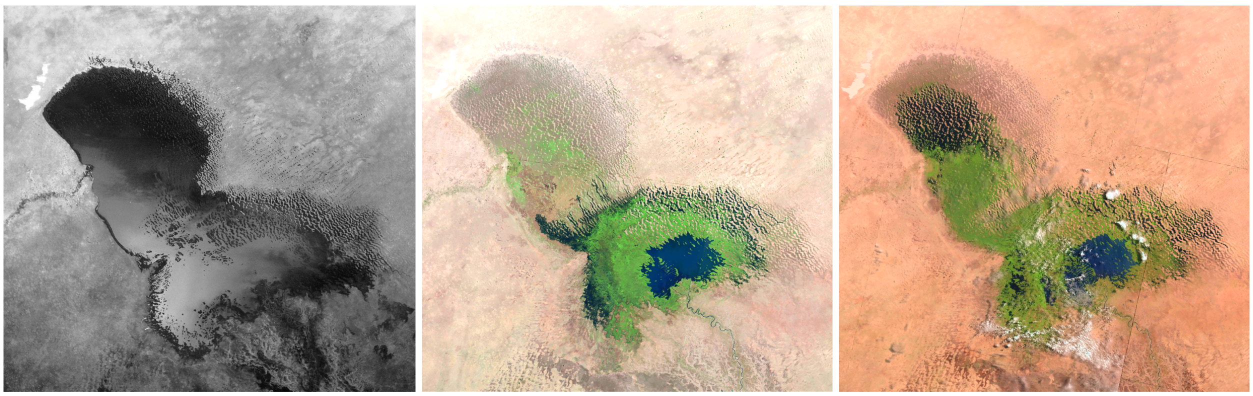
We focus our analysis on four countries that were low-income economies for most of the 20th century and whose territory borders Lake Chad: Cameroon, Chad, Niger, and Nigeria. These countries account for 25% of the population of sub-Saharan Africa today. The shrinkage of the lake starting in 1963 had to do with reduced rainfall in a fifth country more than 800 km away from the lake itself, the Central African Republic (CAR) (see Figure 2 below). This is because two major rivers – the Chari and the Logone – flow from the CAR through Chad and into Lake Chad, which is a sink. Once one controls for proximity to these rivers, the lake’s drying is plausibly exogenous to local conditions.

To conduct our analysis, we use original census and administrative count data to construct a novel data set tracking population patterns at a fine spatial level over

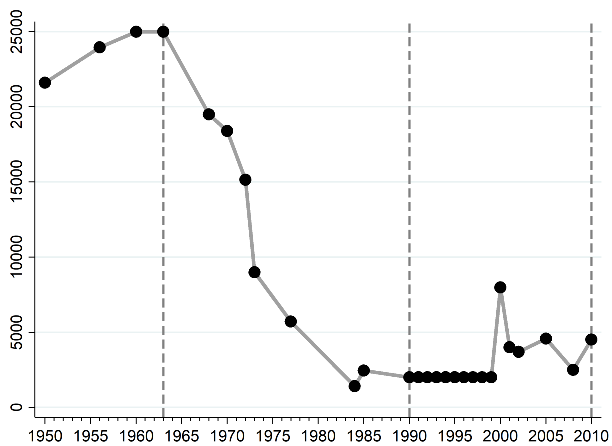
70 years: 113, 138, 119, and 83 subdistricts in Cameroon, Chad, Niger, and Nigeria, respectively (see Figure 2). For each country, we then use (relative) population growth as our outcome of interest, finding in a panel difference-in-difference (DiD) framework: (i) no differential effect of proximity to the lake before 1963; (ii) a very negative effect of proximity to the lake in 1963-1990; and (iii) an effect that remains strongly negative post-1990. In the long run, locations close to the lake have been growing ≈ 45% slower than other locations in Chad, and ≈ 30% slower in the other countries.

Figure 1: Evolution of Lake Chad, 1960-2010

(a) c. 1960 (Full Lake; 1963) **(b)** c. 1990 (Medium-Run; 1987) **(c)** c. 2010 (Long-Run; 2013)



(d) Surface Water Area (Sq Km; 1 Sq Km ≈ 0.40 Sq Mi)



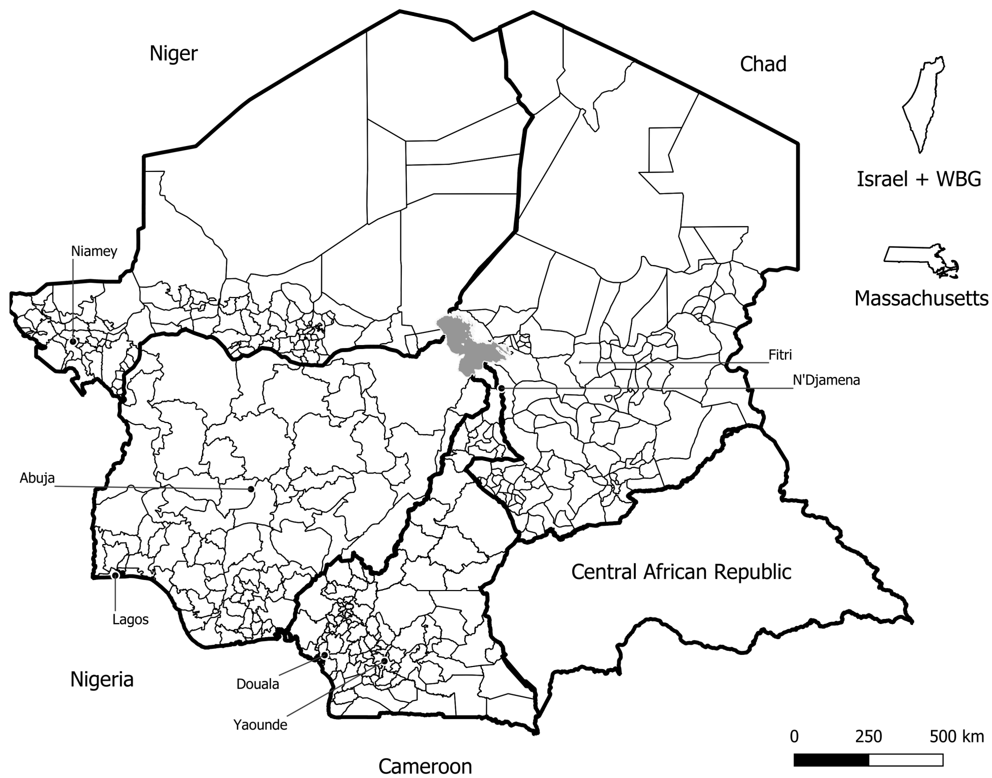
Notes: Subfigures (a)-(c) show the evolution of Lake Chad from c. 1960 to c. 2010. Sources: (a) USGS EROS Archive - Declassified Data - Declassified Satellite Imagery – 1 (1963); (b) covers the period 01-31-87 / 02-09-87 and comes from the Landsat 4-5 TM C2 L1 data set; and (c) covers the period 05-14-13 / 05-23-13 and comes from the Landsat 8 OLI/TIRS C2 L1 data set. All cited data courtesy of the U.S. Geological Survey. See Data Appendix Section B for details on the sources use to construct subfigure (d).

90 percent of rainfall comes from the evaporation of oceans, seas, and lakes (USGS, 2021a). In warmer climates, lakes also have a cooling effect on their direct environment.[1] Therefore, when a large lake dries out, it may permanently alter climate conditions. Lake Chad is an endorheic lake, meaning that it loses most of its

[1]USGS (2021b) writes: "The oceans and lakes help regulate the temperature ranges that billions of people experience in their towns [...]. Water [...] takes longer to heat up and longer to cool down than do land masses, so cities near the oceans will tend to have less change and less extreme temperatures."

water through evaporation. The DiD suggests that rainfall decreased and temperature increased close to the lake. Thus, (global) climate change begets (local) climate change.

Figure 2: Location of Lake Chad and Subdistrict Boundaries for the 4 Countries of Study



Notes: Lake Chad is in the middle across the four countries. Cameroon, Chad, Niger and Nigeria are divided into 113, 138, 119, and 83 subdistricts, respectively (453 subdistricts in total). We show the location of the capital/most populated city of Niger (Niamey) and Chad (N'Djamena). For Cameroon and Nigeria, we show their capital city (Yaounde; Abuja) and largest city (Douala; Lagos).

Our interpretation of the results is that the fishing, farming, and herding sectors were negatively impacted by the lake's receding. As real incomes and welfare decreased in the area, households likely migrated away to other areas. Therefore, the negative effects of the loss in water supply, the lake's direct or indirect input in the three sectors, must have in our context outweighed the positive effects of increased land supply.

To rationalize the effects and study the aggregate impact of the shock, we develop a quantitative spatial model (QSM) with 453 subdistricts and 4 sectors: fishing, farming, herding, and an urban sector. We use data c. 1963 to calibrate the set of parameters and solve the model before, during, and after the lake's shrinkage, taking into account various mechanisms by which it may have affected sectors and amenities. The model explains 75% of the reduced-form shock in the long run, with the other 25% likely explained by conflict due to the shock and other factors that we do not model. Connecting the QSM with the reduced-form allows us to validate the QSM, lending credence to our aggregate loss estimates. Losses reach $\approx 6\%$ for the region (9% in Chad and 5% in other countries). Results hold when considering alternative parameters, expenditure functions/shares, non-homothetic preferences, or the rest of the world.

The QSM also allows us to improve our understanding of the economic effects of lake disappearances. We discuss why the fishing shock was strong, and the land supply effect was not so strong in our context. Estimating the QSM at different points in time – years after the shock started, just after it ended, and 20 years after it ended – also helps examine the possibility of adaptation to reduce CC losses in Africa. We find evidence for limited recovery even decades after the lake stopped shrinking. More generally, we use our validated QSM to study the four countries' respective effects of past CC (e.g., higher temperatures) since the 1950s and future CC until 2070, finding losses of $\approx$ 10-15% and $\approx$ 10-25% when assuming similar levels of (non-)adaptation as observed for Lake Chad.

Finally, we use our QSM to study the aggregate and spatial effects of policies related to (i) migration, (ii) land use, (iii) trade, (iv) roads, and (v) cities. Our study sheds light on the development community's ability to mitigate the losses from lake disappearances and CC in Africa. (i) Allowing for free migration within the region reduces losses by less than 25%;[2] (ii) Promoting land development in former lake areas, for example by creating property rights, does not substantially reduce losses, even when we assume that the freed land is highly suitable for crop cultivation and pastoralism; (iii) Lower trade costs within the region marginally reduces losses. Lower trade costs with the rest of the world has more substantial impacts; (iv) Paving roads in lake areas has weaker impacts than paving roads from major cities towards lake areas; and (v) Increasing the capacity of cities to absorb lake refugees has small effects. Lastly, policies aimed at restoring Lake Chad to its former glory, via mega-engineering projects diverting water from the Congo River basin to Lake Chad, are not economically sustainable.[3]

Overall, adaptation behaviors and policies have limited impacts in our context, which has broad implications for the poorest countries' capacity to face CC theats.

In terms of contributions, our focus on a natural experiment that "mimics" CC and our data-validated QSM analysis allow us to combine the advantages of the empirical and theoretical (predictive) strands of CC and economic development literature.

Reduced-form studies have typically relied on climate deviations across years or groups of years to obtain causality and have studied the following outcomes: economic and agrarian development (Mendelsohn et al., 1994; Schlenker et al., 2005; Deschenes and Greenstone, 2007; Burgess and Donaldson, 2010; Burke et al., 2015b; Hsiang and Meng, 2015; Burke and Emerick, 2016; Dingel et al., 2019; Balboni et al., 2021), conflict (Miguel et al., 2004; Hsiang et al., 2011; Burke et al., 2015a; McGuirk and Burke, 2020; McGuirk and Nunn, 2020), mortality (Deschenes and Moretti, 2009; Deschenes and Greenstone, 2011; Barreca et al., 2015; Carleton et al., 2020), and migration and

[2] Free migration reduces losses even less in the case of past or future CC-driven temperature increases and rainfall decreases, as such changes are more spatially uniform than the lake shock, which thus provides an upper bound of the potential of place-based policies to mitigate the effects of CC

[3] The intergovernmental Lake Chad Basin Commission has for example lobbied the U.N. in order to fund the Transaqua project whose cost is US$50 billion (Sayan et al., 2020; The Conversation, 2021).

structural change (Deschenes and Moretti, 2009; Bohra-Mishra et al., 2014; Cattaneo and Peri, 2016; Colmer, 2021; Albert et al., 2021). In contrast, we study a CC event that unfolded gradually over three decades, taking into account adaptation. Also, most reduced-form studies estimate local effects instead of aggregate losses and policy effects. We use a spatial-economic model and combine both approaches.[4]

Most CC studies using spatial-economic models focus on the world or the U.S. and/or do not link their model to reduced-form evidence (Desmet and Rossi-Hansberg, 2015; Costinot et al., 2016; Conte et al., 2021; Desmet et al., 2021; Conte, 2021; Cruz and Rossi-Hansberg, 2021; Cruz, 2023; Bilal and Rossi-Hansberg, 2023).[5] Most of these studies focus on the effects of *future* temperatures/sea level rise. In contrast, we study the effects of a CC event since the 1960s. Studying the effects of past CC, including the effects of a lakes' disappearance on fishing and herding, can help researchers improve their predictive analysis of future CC impacts. These sectors and shocks have not been included in the previous analyses. Lastly, our QSM performs well in our *historical* context, which gives credence to QSM-based analyses of CC.

We are one of the first studies to combine a natural experiment and a QSM to study the effects of CC in Africa, which remains the most vulnerable continent. We focus on four African countries among the most likely to be impacted by CC in the future. Unfortunately, these countries are also characterized by a dearth of historical, localized, economic data. Nonetheless, we show that with our data compiling effort and methodology it is still possible to study the effects of CC in data-poor countries. Studies have shown that CC is a major driver of conflict, epidemics and poverty there (Burke et al., 2009; Hsiang and Meng, 2014; McGuirk and Burke, 2020; McGuirk and Nunn, 2020; Conte, 2021; Archibong and Annan, 2022; Couttenier et al., 2023). Other literature on the determinants of Africa's lack of economic development have examined the roles of the slave trade (Nunn, 2008; Nunn and Wantchekon, 2011), colonial institutions (Michalopoulos and Papaioannou, 2016; Archibong and Obikili, 2020), technology (Yanagizawa-Drott, 2014; Jedwab and Moradi, 2016), trade costs (Atkin and Donaldson, 2015; Jedwab and Storeygard, 2022), and culture (Moscona et al., 2020; Cao et al., 2021).

Additionally, to our knowledge this is the first paper studying the effects of a shrinking lake on economic development. As such, unlike existing studies on sea level rise and coastal flooding (e.g., Kocornik-Mina et al., 2020; Desmet et al., 2021; Michaels et al., 2021; Hsiao, 2023), we study the effects of water disappearing, not submerging land and roads (as in Balboni (2021)). Floodings lead to crop losses and destruction in cities. Lake recessions, in theory, have more ambiguous effects because potentially valuable land becomes available. However, the emergence of new land raises questions

[4]See Hsiang and Kopp (2018b), Carleton and Hsiang (2016) and Dell et al. (2014) for surveys.

[5]Exceptions such as Bilal and Rossi-Hansberg (2023) and Cruz (2023) study climate "shocks." Some studies also use models other than QSMs (Hsiang et al., 2017; Deryugina and Hsiang, 2017; Nath, 2022).

regarding property rights and other aspects of rural land development, similar to studies of frontier economies (Pellegrina and Sotelo, 2021; Nagy, 2023).[6]

Lake disappearances are important to study in and of themselves. Lakes are major economic assets for many world regions, covering 4% of Earth's nonglaciated land area (Verpoorter et al., 2014).[7] Africa has 10 of the 50 largest lakes in the world and "Africa's lakes contribute significantly to the continent's socio-economic development" (UNEP, 2006). Examples of drying lakes include the Aral Sea (Kazakhstan, Uzbekistan), formerly the 4th largest lake in the world, and Lake Urmia (Iran), formerly the largest lake in the Middle East. In the U.S., the Great Salt Lake has lost two-thirds of its area, as a result of which "Utah faces an 'environmental nuclear bomb" (New York Times, 2022).[8] Likewise, the dry lakebed of the disappeared Salton Sea in Southern California has become "the biggest manmade source of hazardous dust in the U.S." (The Atlantic, 2015).[9]

Climate change is a multi-faceted phenomenon (Hsiang and Kopp, 2018a) and many lakes and rivers are drying in the world due to CC (UNEP, 2006; The Guardian, 2023);[10] Appx. Section A provides 25 more global examples of drying lakes and rivers). Economic analyses of the costs, but also benefits, of these trends are needed. As such, our paper is related to literature on the effects of natural disasters (Kahn, 2005; Boustan, Kahn and Rhode, 2012; Hornbeck, 2012; Sacerdote, 2012; Hornbeck and Naidu, 2014; Guiteras, Jina and Mobarak, 2015; Boustan, Kahn, Rhode and Yanguas, 2020; Henkel, Kwon and Magontier, 2022; Balboni and Boehm, 2023). Both our study and some others show that migration is one method by which countries adapt to climate-related shocks. However, the shocks considered in these studies lasted no more than a few years. Most studies are also reduced form in nature and do not quantify aggregate losses and policy effects.

The paper is structured as follows: Section 1. provides the background. Section 2. introduces our novel data. Sections 3. and 4. present the reduced-form results. Section 5. and 6. present the QSM analysis and policy results. Section 7. concludes.

1. Background: Why Lake Chad Shrunk

Lake Chad is a sink that receives water from the Chari-Logone river system (see Fig. 3 below). The river system primarily originates from heavy rainfall in the mountainous areas of the Central African Republic (CAR) more than 800 km away from the lake itself (South-East corner in the map). Rainfall in Eastern Cameroon and rainfall in the Southeastern areas of Chad marginally contribute to the system (Magrin et al., 2015;

[6] There is literature on the importance of water for rural development. However, most studies focus on groundwater (e.g., Sekhri, 2014; Hornbeck and Keskin, 2014; Blakeslee et al., 2020, 2023).

[7] This includes the Caspian Sea in Eurasia and Lakes Victoria, Tanganyika, and Malawi in East Africa.

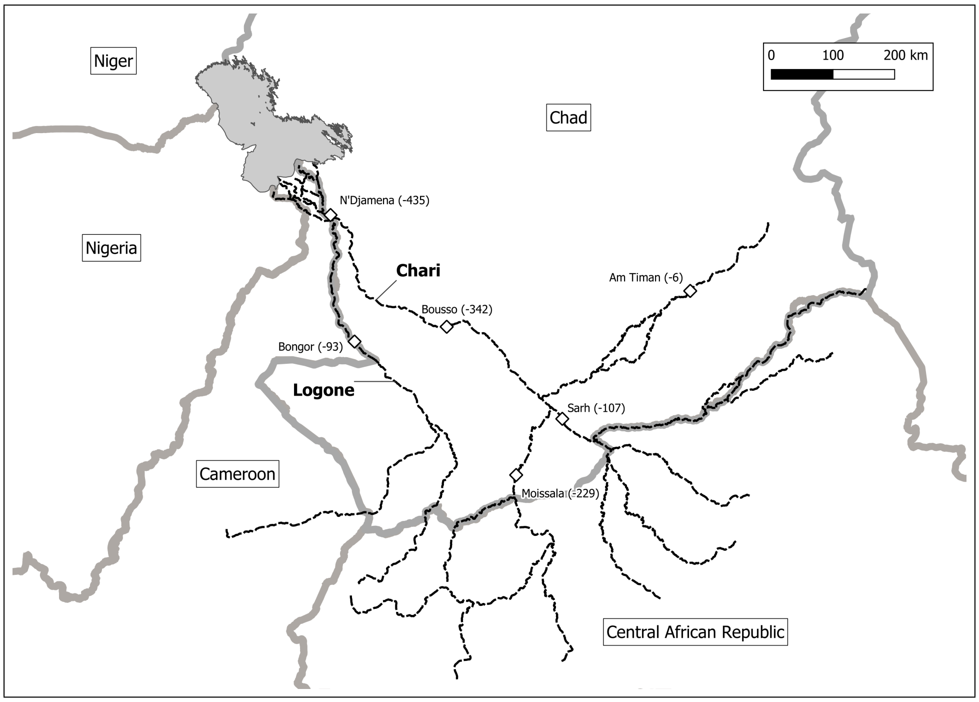
[8] The New York Times (2022) writes: "Climate change and rapid population growth are shrinking the lake, creating a bowl of toxic dust that could poison the air around Salt Lake City."

[9] The Atlantic (2015) writes: "LA has spent more than $1.2 billion dollars trying to suppress the dust."

[10] The Guardian (2023) writes: "More than half of the world's large lakes and reservoirs have shrunk since the early 1990s – chiefly because of the climate crisis [...] intensifying concerns about water supply"

Pham-Duc et al., 2020). However, because the discharge rate of the Chari and Logone rivers depends almost exclusively on rainfall in Northern CAR, lack of rainfall over the CAR after 1962 – due to global climate change disproportionately impacting Central Africa starting in the 1960s – was by far the main reason behind the drop in water area observed from 1963 (Fig. 2) (Evans and Mohieldeen, 2002; Magrin et al., 2015; Pham-Duc et al., 2020). See Appx. Section C for details on the exact timing of these patterns.[11]

Figure 3: Rivers of the Chari-Logone River System Feeding Lake Chad



Notes: We show in bold the main rivers of the Chari-Logone river system that provides almost all of Lake Chad's water. We also show for selected upstream sites of the Chari-Logone river system the absolute reduction in the mean flow rate (m^3/s) between the period 1950-1964 and the period 1965-1980. See Appx. Sections B and C for details on the sources and mean flow rate analysis, respectively.

The fact that the lake's water level is primarily determined by rainfall in another country south of our region of study provides reassurance that the results will not be explained by reverse causality. However, this does not rule out other sources of bias.

Because the Chari and Logone rivers go through the territory of Cameroon and Chad, less rain in the CAR may have affected other locations along the river system. Control areas farther away from the lake are then also affected. Yet, this should only lead us to underestimate how negative the local effects of the lake's shrinkage are.

Furthermore, historical data on discharge rates for various sites along the river system from the 1940s to the 1980s suggest that the decline in discharge rates started in 1963, at the same time as rainfall began declining in the CAR. As seen in Figure 3, which

[11] Appx. Fig. E.1 shows stable rainfall patterns before 1963 and far stronger rainfall declines after 1963 in the mountainous areas of the Central African Republic than in the subdistricts close to Lake Chad in the four countries of study (Cameroon, Chad, Niger, Nigeria). For these areas, the decline in rainfall can be observed from 1970, at least seven years after the lake started shrinking. We show later that the post-1963 decrease in rainfall close to Lake Chad was mostly due to the drying of the lake itself.

shows the sites and the decline in their mean annual discharge rate between before and after 1963, most of the collapse close to the lake – in N'Djamena (-435 m^3/s annually) – came from the Chari River (Bousso: -342). The contribution of the Logone River was more limited (Bongor: -93). In turn, almost all the decline in the Chari River came from the CAR, not Chad. Am Timam in Chad shows a decrease of only 6 m^3/s vs. 107 for Sarh and 229 m^3/s for Moissala, the two entry points of the CAR's rainfall into the Chari.[12]

Also, recent studies document that irrigation withdrawals and anthropogenic activities barely contributed to overall water losses (Pham-Duc et al., 2020; Nour et al., 2021). To conclude, the decline of rainfall in a fifth country, CAR, was behind the lake's shrinkage (Magrin et al., 2015; Nour et al., 2021). Nevertheless, we will control for proximity to the Chari-Logone river system throughout the analysis.[13]

The river system is also not present in Niger or Nigeria, making these two countries potentially cleaner environments for our analysis. However, some minor rivers of the Chari-Logone system follow the Cameroon-Nigeria border (Web Appx. Fig. E.2). As such, we will control for proximity to the extended Chari-Logone river system in Nigeria.

Note that we will find relatively similar local growth patterns for the four countries, giving us confidence that we are effectively controlling for any potential bias generated by rivers. This also reassures us about the external validity of our results.

Splitting Lake Chad in half lies what is called the *Grande Barrière*, an elevated area that in dry years divides the lake into two. It is only when the water level of the southern pool is high enough that water crosses the Grande Barrière (Evans and Mohieldeen, 2002; Pham-Duc et al., 2020). As the Chari-Logone Rivers' discharge rate declined, the Grande Barrière created a northern sink that dried almost completely and a southern sink that retained some water (Fig. 1) (Magrin et al., 2015). We will exploit this fact below.

2. Data for the Reduced-Form Analysis

An analysis of the impact of the lake's drying demands localized data for the period 1963-2010 and the pre-1963 period. Due to data scarcity, *subdistrict total population* figures are the best measures available. Demographic/household/labor force surveys are not available before the mid-1990s. Likewise, only the 1976, 1987, and 2005 population censuses of Cameroon are available on IPUMS (the lake's level was already low by 1976). Nighttime lights are only available from the year 1992. Finally, the various censuses that took place over time in each country are not consistent with each other, constraining our ability to track other outcomes over such a long period. Data on land values also does not exist. This is a feature of studying the effects of past CC in the poorest countries.

Typically, the sources that we were able to get ahold of report population data at the subdistrict level. As boundaries changed over time, we aggregated subdistricts to

[12] The patterns for each site are discussed in Appx. Section C and shown in Appx. Fig. E.3.

[13] Since Chad's Southern areas are closer to the CAR's mountainous areas, it is safer to also control for the subdistrict's latitude interacted with year fixed effects, which we do for the four countries.

reconstruct a set of consistently defined subdistricts over periods spanning 60-70 years. Our data set contains 119 subdistricts for Niger (1951-2012), 113 for Cameroon (1963-2005), 138 for Chad (1948-2009), and 93 for Nigeria (1952-2006) (Fig. 2 above).[14]

In Niger (119 subdistricts), we have total population data in 1951, 1956, 1959, 1962, 1969, 1988, 2001, 2012, 2013, and 2017. Data for the years 1951, 1956, 1959, 1962, 1969, 2013, and 2017 come from administrative sources (often administrative censuses). Values for the years 1988, 2001, and 2012 come from population censuses.[15]

The Cameroon data set (113 subdistricts) includes the years 1963 and 1967 (administrative sources) and 1976, 1987, and 2005 (population censuses). No census has taken place since 2005. We only have population data for one year before the lake started shrinking. To examine whether the parallel trends assumption holds for Cameroon, we will add the year 1956 by using total population data at the district level (47 districts).

The Chad data set (138 subdistricts) includes the years 1948, 1953, 1963, 1993, and 2009. Measures for the years 1948 and 1953 are based on administrative sources. For the year "1963", we use information from the 1962 administrative census and the 1964 *Enquête Démographique*.[16] Lastly, we use census figures for the years 1993 and 2009.

Finally, the Nigeria data set (83 subdistricts) includes the years 1952, 1963, 1991, and 2006. However, the reliability of the 1963 census has been questioned by experts (Ahonsi, 1988). The results of the 1973 census were also never published (Ibid).

The mean subdistrict is 4-11 thousand sq km (the mean U.S. county is 3 thousand sq km). Were the subdistricts shaped like circles, their radius would be 36-59 km.

3. Reduced-Form Effects

The historical drop in water levels starting in 1963 and ending c. 1990 allows us to examine the effects of the shrinking lake on nearby communities at different points in time. To do so, we exploit a simple panel difference-in-difference (DiD) framework and study the effect of proximity to the lake on total population patterns. For subdistricts s and years t and *each country at a time*, we estimate the following model:

$$ln(Tot.Pop.)_{s,t} = \alpha + \sum_{v} \beta_v Prox.Lake_s \times \mathbb{1}(v=t) + \lambda_s + \theta_t + D_s * t + X_s B_t + \mu_{s,t}. \quad (1)$$

$ln(Tot.Pop.)_{s,t}$ is log population. The variables of interest are the interactions between the time-invariant measure of proximity to the lake – log Euclidean distance from each subdistrict's centroid to the centroid of Lake Chad within the country's territory (Appx Fig. E.4) – and year dummies (we omit the latest year available before 1963).

We add subdistrict (λ_s) and year (θ_t) fixed effects, as well as district-specific linear

[14] *Communes* in Niger, *arrondissements* in Cameroon, *sous-prefectures* in Chad, and *divisions* in Nigeria.

[15] Boko Haram started its terrorist insurgency in North-Eastern Nigeria in July 2009, which our population estimates predate. Since it spread to Niger in 2014, it is fine to consider its 2012 census.

[16] A few subdistricts have incomplete 1963 data. We adjust their estimates using a 1968 administrative count that only covered a few regions. That should if anything lead to more conservative estimates.

trends ($D_s \times t$) to control for regional patterns of economic development over time (similar to U.S. states). We use Conley standard errors (distance cut-off of 100 km).[17]

Furthermore, our specification includes several time-invariant controls (X_s) that we interact with year effects. We add the logged Euclidean distances to the largest city and the capital city, and their square.[18] This flexibly controls for spatial development patterns related to nation-building and political and economic centralization as documented by Herbst (2000) and Bates (1981) in post-independence Africa.[19]

For historical reasons, northern areas are less developed, and have been growing slower, than southern areas in the four countries (Boone and Simson, 2019; The World Bank, 2020). Geography also varies with latitude, with declining vegetation density as one moves north and, in the case of Chad and Niger, desertification (Mortimore, 1989). We thus interact the latitude of the subdistrict's centroid with year fixed effects.

We add dummies for whether the subdistrict is crossed by a major river or a minor river (Appx. Fig. E.2) of the Logone-Chari river system, interacted with year dummies.

Finally, Nigeria discovered oil in the 1950s, which dramatically increased spatial inequality (Zainab, 2022). We add various controls interacted with year dummies: (i) a dummy if there were oil deposits c. 1960;[20] (ii) the logged Euclidean distances to Port Harcourt and Benin City, the capital cities of the oil-rich Delta region, and their squares; and (iii) the logged Euclidean distance to Kano, the North's capital, and its square. A large share of oil revenues is indeed shared with the Delta and Northern regions.

Niger offers the best environment for this analysis. Its territory does not contain any river of the Chari-Logone system, and we have more years of data (119 subdistricts x 17 years = 2,023 obs.). Figure 4(a) below shows the effects (β_v) of proximity to the lake in each year (1962 is the omitted year). The pre-1963 patterns suggest parallel trends.

Table 1 below shows the short-term effects c. 1970 – less than ten years after the lake started shrinking –, medium-term effects c. 1990 – when it stopped shrinking,– and long-term effects c. 2010 – two decades after it stopped shrinking.– c. 1970 (1969), we see a negative effect of -0.23** ((exp(-0.23)-1)*100 = -21%). By then, Lake Chad had shrunk by $\approx$20%. The effect is more negative c.1990 (1988), at -0.41*** (-34%; shrinkage $\approx$90%). Being 10% closer to the lake results in a 3.4% relative decline in population. Alternatively, one standard deviation in proximity to the lake leads to a 0.48 standard deviation decrease in the log population. The effects remain high c. 2010 (2012; -0.33*; -28%). Confidence intervals expand over time as some lake locations declined slower than others, implying heterogeneity in the impacts. Our QSM replicates these patterns.

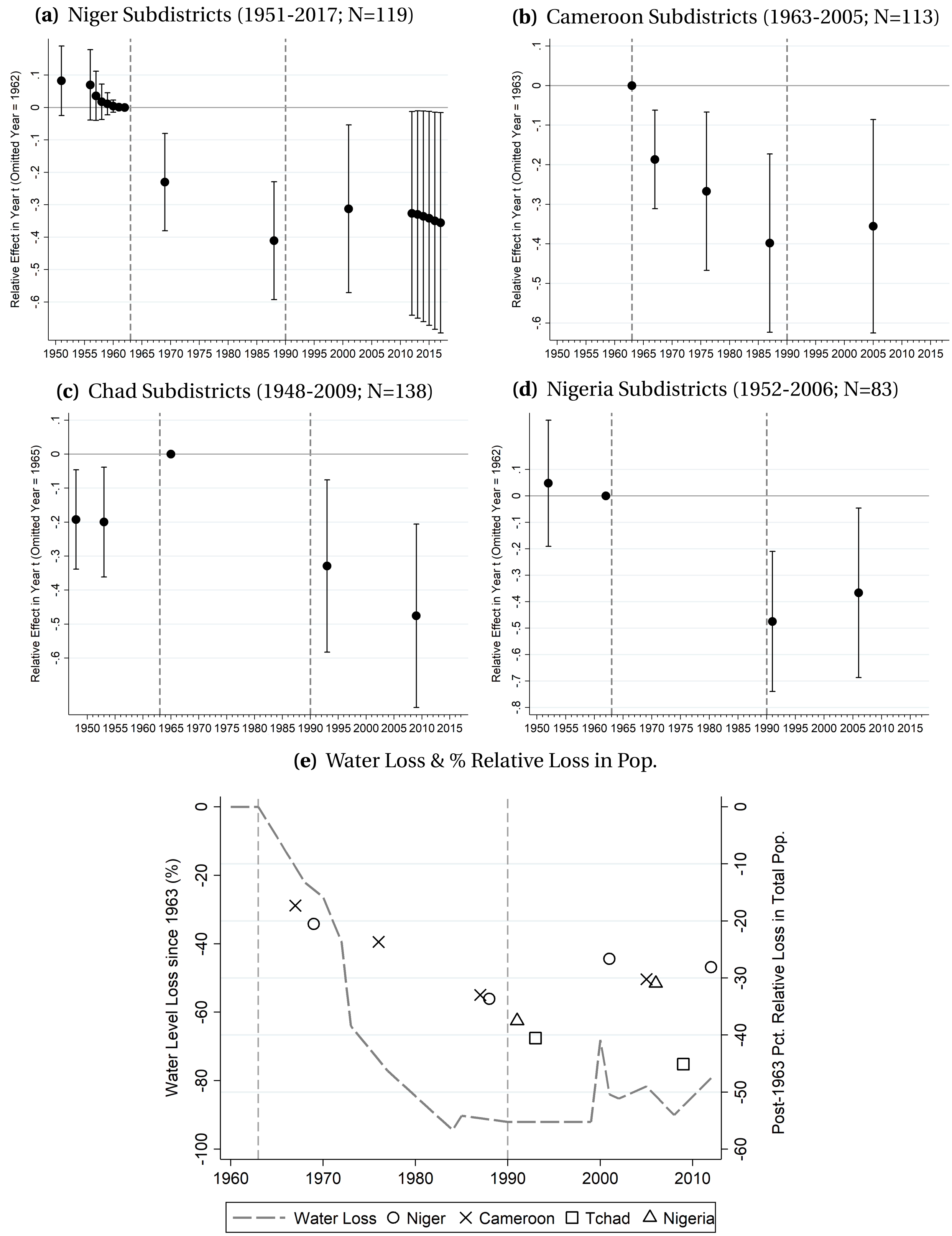
[17] We consider 31, 47, 36, and 24 districts in Niger, Cameroon, Chad and Nigeria, respectively. The district boundaries more or less correspond to *departements, prefectures* or *states* in the 1960s.

[18] The largest city is not the capital city in Cameroon (Douala vs. Yaoundé) and Nigeria (Lagos vs. Abuja).

[19] For Chad, we add a dummy if 1968 information was used for the year 1963 (interacted with year FE).

[20] The source is *Petrodata* from Prio. Accessed 06-17-2022. Url: https://www.prio.org/data/11.

Figure 4: Relative Total Population Effect of Proximity to Lake Chad, 1950s-2010s



Notes: Subfig. (a)-(d) show for each country the relative total population effects of proximity to Lake Chad (relative to the omitted year shown at left). Niger (1951-2017): 119 subdist. x 17 yrs = 2,023. Cameroon (1963-2005): 113 subdist. x 5 yrs = 565. Chad (1948-2009): 138 subdist. x 5 yrs = 690. Nigeria (1952-2006): 83 subdist. x 4 yrs = 332. We include subdistrict and year FE, district-specific linear trends, and time-invariant controls interacted with year FE (see text for details). 90% confidence intervals (Conley SEs 100 Km). The dashed vertical lines show the years the lake started to decline (c. 1963) and stopped shrinking (c. 1990). Subfig. (e) plots the percentage of water loss and the relative percentage of population loss in each year (relative to the pre-1963 year).

Results hold if we (Appx. Table E.1): (i) Use the full lake's centroid (Appx. Fig. E.4); (ii) Add a dummy if the subdistrict contains the Komadugu-Yobe River, interacted with year dummies. It is a small river that follows the Niger-Nigeria border and flows into the lake;[21] (iii) Control for rainfall and temperature in $[t\text{-}2;\, t]$ and their square, in case some of the shrinkage was driven by local weather conditions; and (iv) Use 250 km Conley SE.

Table 1: Reduced-Form Effects, Total Population, 1950s-2010s

Dependent Variable:		Log Subdistrict Population in Year t			
(Relative to the c. 1963 Omitted Year)		Niger	Cameroon	Chad	Nigeria
Short-Term:	Proximity to Lake (log)*c.1970	-0.23**	-0.19**	–	–
		[0.09]	[0.08]	–	–
Medium-Term:	Proximity to Lake (log)*c.1990	-0.41***	-0.40***	-0.54***	-0.47***
		[0.11]	[0.14]	[0.08]	[0.16]
Long-Term:	Proximity to Lake (log)*c.2010	-0.33*	-0.36**	-0.62***	-0.37*
		[0.19]	[0.16]	[0.17]	[0.19]
Subdistrict Fixed Effects, Year Fixed Effects		Y	Y	Y	Y
District-Specific Linear Trends, Controls		Y	Y	Y	Y

Notes: Niger: 119 subdistricts x 17 years (1951-2017) = 2,023 observations. c. 1970 = 1969. c. 1990 = 1988. c. 2010 = 2012. Cameroon: 113 subdist. x 5 years (1963-2005) = 563 obs. c.1970 = 1967. c.1990 = 1987. c.2010 = 2005. Chad: 138 subdist. x 5 years (1948-2009) = 690 obs. c.1990 = 1993. c.2010 = 2009. Nigeria: 83 subdist. x 4 years (1948-2009) = 332 obs. c.1990 = 1991. c.2010 = 2006. *Proximity to Lake* is the negative of the log Euclidean distance to the centroid of Lake Chad within the country's territory (Appx Fig. E.4). See text for details on the controls. Conley SEs 100 Km ((5): 250 km). *** p<0.01, ** p<0.05, * p<0.1.

The model allows us to estimate only one coefficient per year. We now use a version of eq. (1) where we employ three dummies based on the Euclidean distance between a subdistrict's centroid and the centroid of the lake area that is within Niger's territory, which we interact with the year dummies. We choose 0-150, 150-300 and 300-450 km:[22]

$$\begin{aligned} ln(Tot.Pop.)_{s,t} = \alpha + \sum_v \beta_{150,v} Lake_{150} \times \mathbb{1}(t=v) + \sum_v \beta_{300,v} Lake_{300} \times \mathbb{1}(t=v) \\ + \sum_v \beta_{450,v} Lake_{450} \times \mathbb{1}(t=v) + \lambda_s + \theta_t + X_s B_t + D_s * t + \mu_{s,t} \end{aligned} \tag{2}$$

Table 2 below reports the main effects. We find strong negative effects within 150 km (2001; (exp(-0.63)-1)*100) = -47%). The effects for 150-300 km are less strong than the effects within 150 km. Likewise for the 300-450 km bin relative to the 150-300 km bin.[23]

We find no pre-trends and similar results for Cameroon, Chad, and Nigeria (Fig. 4 for the graphical results, Table 1 for the main effects, and Table 2 for the bin specification).[24]

The robustness checks for Cameroon, Nigeria, and Chad are shown in Appx. Tables E.2, E.3, and E.4, respectively. Regarding Chad, it contains in its territory portions of

[21] Its annual discharge rate has been stable around 15 m^3/s and no change occurred c. 1963 (Martinsson, 2010). The discharge rate for the Logone-Chari close to the lake was ≈1,400 m^3/s pre-1963.

[22] Appx. Fig. E.6 shows the selected subdistricts and confirms that selecting up to 450 km is reasonable.

[23] Were the subdistricts shaped like circles, their radius would be about 36-59 km. We cannot consider bins that are too small (e.g., 50 km). Likewise, if the bins are too large (250 km), we may miss local effects.

[24] We only have one pre-1963 year (1963) for Cameroon. Relying on 47 districts instead adds the year 1956 to the analysis. Using the same specification as for subdistricts, people were moving closer to the lake before 1963 (Appx. Fig. E.5). If there is a pre-trend, our estimates are conservative estimates.

both the northern and southern pools of the lake. Appx. Table E.4 shows less negative effects if the lake centroid is defined using the southern pool, likely due to migration from the dried-out northern pool to the never-completely dry southern pool. For Chad, we also utilize Lake Fitri as a placebo check of our analysis (Fig. 2 shows its location). Lake Fitri has not shrunk and no negative effect is indeed found for it (Appx. Table E.4).[25]

Table 2: Reduced-Form Effect, Four Countries, Distance Bins

Dependent Variable:	Log Subdistrict Population in Year t			
Omitted Year = Early 1960s	Niger	Cameroon	Chad	Nigeria
Lake 0-150 Km Dummy*c.1970	-0.41***	-0.45***	-	-
	[0.07]	[0.13]	-	-
Lake 150-300 Km Dummy*c.1970	-0.13**	-0.30***	-	-
	[0.06]	[0.10]	-	-
Lake 300-450 Km Dummy*c.1970	0.09	-0.26***	-	-
	[0.06]	[0.10]	-	-
Lake 0-150 Km Dummy*c.1990	-0.64***	-1.22***	-0.85***	-0.82*
	[0.08]	[0.23]	[0.28]	[0.44]
Lake 150-300 Km Dummy*c.1990	-0.60***	-0.85***	-0.76***	-0.19
	[0.08]	[0.13]	[0.22]	[0.27]
Lake 300-450 Km Dummy*c.1990	-0.07	-0.88***	-0.36***	0.00
	[0.05]	[0.13]	[0.12]	[0.16]
Lake 0-150 Km Dummy*c.2010	-0.63***	-1.41***	-0.91***	-0.99***
	[0.15]	[0.27]	[0.40]	[0.29]
Lake 150-300 Km Dummy*c.2010	-0.42***	-0.98***	-0.73**	-0.96***
	[0.09]	[0.09]	[0.34]	[0.24]
Lake 300-450 Km Dummy*c.2010	-0.05	-1.08***	-0.37**	0.02
	[0.08]	[0.06]	[0.16]	[0.02]
Subdistrict FE, Year FE	Y	Y	Y	Y
District Linear Trends, Controls	Y	Y	Y	Y

Notes: See the notes of Table 1 for details on the samples. See text for details on the controls. Conley SE 100 Km.

Results generally hold if we exclude (Appx. Table E.5): (i) the river controls; (ii) the city controls; and (iii) the oil controls, which concerns Nigeria. We exploit one large spatially concentrated shock instead of multiple spatially scattered small shocks. In the specification where logged distance to the lake is the variable of interest, trends and shocks in locations farther away from the lake might also impact the estimates. The controls contribute to minimizing any influence from broad spatial factors that are not captured when testing for parallel trends. Our estimates are cleaner with controls. Lastly, the bin specification allows us to compare shore locations (0-150 km) and lake locations farther away (150-300 and 300-450 km) for which we find lower impacts.

Figure 4(e) shows the percentage water loss and the estimated (relative) percentage population losses for the four countries. The average population loss in the short-run

[25] Lake Fitri's size depends on rainfall in bordering Sudan (Hughes et al., 1992). Chad's results also hold with a dummy for whether the subdistrict contains the Bahr el-Ghazal – a dry riverbed that was pre-1900 an outflowing river of Lake Chad (Collelo, 1988) – interacted with year dummies (Appx. Table E.4).

(c. 1970) was ≈19% (mean elasticity of -0.21). In the medium-run (c. 1990), we get ≈36% (mean elasticity of -0.46). In the long-run (c. 2010), we get ≈34% (mean elasticity of -0.42). The long-run effect is then more negative for Chad (-46%; elasticity of-0.62).

A strong effect appears as early as c. 1970. As we will show in the QSM analysis, a major effect of the lake's drying was to deprive long-established fishing communities of their direct access to the lake. If a lake's shore recedes, a fishing village likely loses its economic function. N'guigmi, Niger's largest town in the vicinity of the Lake, was in the mid-20th century a "centre of Kanuri fishing communities" (Geels, 2006). During the mid-1970s the lake's shore was 85 km away from it.[26] Consistently, Table 2 shows that the relative effects for the lake shore locations (0-150 km) vs. the other lake locations (> 150 km) were larger c. 1970 than c. 1990 or c. 2010. Thus, the effects of the lake's drying were disproportionately along the shore initially and spread out across space over time.

More generally, we find similar spatial patterns in the four countries, which should assuage concerns related to causality, measurement error, and external validity.

4. Other Reduced-Form Effects Supporting the QSM

Rural decline. Since rural sectors – fishing, farming, and herding – were reliant on the lake's existence and since lake regions were little urbanized in 1963, population losses were likely driven by rural decline.[27] We thus employ the same panel-DiD model considering log rural population. To construct rural population (total - urban pop.), we obtain the population of cities for each country-year. Following Bairoch (1988), a city is any locality with at least 5,000 inhabitants at any point during the period of study.[28] We focus our data-compiling efforts on localities that reached 5,000 inhabitants at any point, relying on population censuses and administrative counts (see Appx. Section D for details). Our selection process yields 186, 100, and 166 cities in Cameroon, Chad, and Niger, respectively. For each city, we know its population when it is above 5,000. For Nigeria, consistent data on localities with 5K+ inhabitants does not exist. We also consider the 20K population mark because towns in the 5K-20K range include a significant share of primary sector workers (e.g., fisher people living in coastal towns).

Overall, we find stronger negative effects for rural populations (Appx. Table E.6) than for total populations (Table 2), especially when considering the 20K threshold. Therefore, the total population decline was essentially driven by rural population

[26]Odada et al. (2003) write: "By the end of the 1960s, drought conditions had started to set in [...] The Lake water receded for more than 150 km from its northern and eastern shores, and by more than 80 kilometers from its western shoreline. Some of the natural fauna and flora disappeared and sand dunes appeared on the dry lake bed [...] fishing, livestock rearing and farming, were adversely affected [...]." DeGeorges (1979) writes: "Both Bol [in Chad] and Baga Kawa, Nigeria have been removed as important fishing centers because of decreased access to the lake from encroachment by aquatic plants and falling lake levels. As a result, the largest and most important fish market since 1973 has been Boulongoa [...]."

[27]The countries' urban shares were 7-17% (UN, 2018). Lake regions were even less urbanized.

[28]The mean population threshold used in the world to define cities is 4,500 (Jedwab and Vollrath, 2015).

decline, justifying our focus on the impacts of rural sectors in the QSM analysis below.[29]
Climate. 90% of rainfall comes from the evaporation of oceans, seas, and lakes (USGS, 2021a). In warmer climates, lakes also have a cooling effect on their direct environment. Thus, when a large lake dries out, it may permanently alter local climate conditions.

Table 3: Effect of Proximity to the Lake, Local Climate Effects, Flexible Specification

Benchmark = 1950-1964	(1) Niger	(2) Cameroon	(3) Nigeria	(4) Chad
Dependent Variable:	Mean Monthly Temperature (Celsius) in the Subdistrict in Period t			
0-150 Km*(1980-1994)	0.38***	0.89***	0.19***	0.19**
	[0.06]	[0.15]	[0.06]	[0.08]
150-300 Km*(1980-1994)	0.16***	0.31**	0.35***	0.06
	[0.06]	[0.15]	[0.07]	[0.07]
300-450 Km*(1980-1994)	-0.22***	0.02	0.10†	0.05
	[0.05]	[0.15]	[0.06]	[0.06]
Dependent Variable:	Log Mean Annual Rainfall (mm) in the Subdistrict in Period t			
0-150 Km*(1980-1994)	-0.08***	-0.26***	-0.13***	-0.25***
	[0.02]	[0.03]	[0.02]	[0.04]
150-300 Km*(1980-1994)	-0.04	-0.05*	-0.18***	-0.20**
	[0.03]	[0.03]	[0.02]	[0.04]
300-450 Km*(1980-1994)	-0.06***	-0.05**	-0.10*	-0.04*
	[0.02]	[0.02]	[0.05]	[0.02]
Subdistrict FE, Period FE	Y	Y	Y	Y
District Trends, Controls	Y	Y	Y	Y

Notes: Obs.: Niger: 119 Subdist. x 13 Periods = 1,547. Cameroon: 113 Subdist. x 13 Periods = 1,469. Nigeria: 83 Subdist. x 13 Periods = 1,079. Chad: 138 Subdist. x 13 Periods = 1,794. We report the difference between the avg. effect for 1980-84 + 1985-89 + 1990-94 and the avg. effect for 1950-54 + 1955-59 + 1960-64 (omitted = 2010-14). Conley SE 100 Km. *** p<0.01, ** p<0.05, * p<0.1, † p<0.15

For each subdistrict-year, we know annual rainfall (mm) and average monthly temperature (°C) (Appx. Section B). Focusing on the post-1950 period, we obtain for each subdistrict the mean of these measures in 13 five-year periods: 1950-54, 1955-59 ... 2010-14. We use the same panel bin specification as eq. (2) but use mean temperature or log rainfall as the dependent variable (we replace year dummies by period dummies). We then interact the three bin dummies with dummies for each period (omitting the interaction for 2010-14). Lastly, as controls, we include latitude and the Chari-Logone river dummies interacted with period fixed effects, as well as the district trends.[30]

Table 3 above reports the difference between the average effect for the full 1980-94 period and the average effect for the full 1950-64 period, which captures long-run climatic changes post-1963. In Niger, Cameroon, Nigeria, and Chad, temperatures increased by 0.0-0.4°C, 0.0-0.9°C, 0.1-0.4°C, and 0.1-0.2°C, respectively. In contrast, the mean temperature increase across the four countries between 1960 and 2010 was +1°C. For rainfall, the elasticity goes from -0.04 to -0.26. In Niger, Cameroon, Nigeria, and Chad, we find losses of 4-8%, 5-23%, 9-16%, and 3-22%, respectively. In contrast, rainfall

[29] The results for urban populations are more ambiguous (not shown but available upon request).

[30] The exact model for subdistrict s and period t is: $Climate_{s,t} = \alpha + \sum_v \beta_{150,v} Lake_{150} \times \mathbb{1}(t = v) + \sum_v \beta_{300,v} Lake_{300} \times \mathbb{1}(t = v) + \sum_v \beta_{450,v} Lake_{450} \times \mathbb{1}(t = v) + \lambda_s + \theta_t + X_s B_t + District_s * t + \mu_{s,t}$.

decreased by 12% on average across the four countries between 1960 and 2010.

The results show how large the lake effects were relative to global CC (we tend to find stronger effects for the subdistricts closest to the lake). Given these countries have low rainfall levels and high temperatures already, these lake effects are meaningful. In the QSM below, we will consider how production sectors and amenities are impacted.[31]

Conflict. The shock possibly increased conflict as incomes decreased and resource competition intensified. Localized conflict data does not exist as far back as the 1950s. However, we use 1997-2019 data from the Armed Conflict Location & Event Data Project (Linke et al., 2010) to examine if conflict correlates with proximity to former lake areas.[32]

Table 4: Proximity to Lake Chad and Conflict, Cross-Sectional Poisson Model

	(1)-(3): Non-Organized Violence			(4)-(6): Organized Violence		
Type:	All	Protests	Riots	All	Battles	Against Civ.
Dependent Variable:	Number of Conflict Events in 1997-2019, Poisson Model					
Lake 0-150 Km	2.26**	1.76†	2.19***	1.85***	1.89***	1.86***
	(1.12)	(1.34)	(0.80)	(0.45)	(0.40)	(0.56)
Lake 150-300 Km	1.44**	1.75**	1.02**	1.26***	1.22***	1.27***
	(0.65)	(0.88)	(0.43)	(0.25)	(0.29)	(0.25)
Lake 300-450 Km	0.36	0.57	0.14	-0.52	-0.60*	-0.55
	(0.48)	(0.64)	(0.32)	(0.38)	(0.33)	(0.39)
Mean	13.69	9.25	4.45	29.79	12.78	14.32
# Non-Zeros	170	139	146	243	203	208
Country FE, Controls	Y	Y	Y	Y	Y	Y

Notes: Obs.: 453. Controls: See text for details. Conley SE 100 km *** p<0.01 ** p<0.05 * p<0.1 † p<0.15

We run regressions whereby the dependent variable is the number of different types of conflict events in a subdistrict during the period 1997-2019 and the variables of interest are the three bin dummies capturing proximity to the lake. Due to the high number of zeros across the 453 units, we use a Poisson model. Since some countries have few conflict events of a certain type, we also run pooled regressions with the four countries altogether (incl. country fixed effects). Lastly, we add a few controls: log area and log population c. 1990, the log of the Euclidean distances to the largest city and the capital city, and their squares, and latitude. We use Conley standard errors (100 km).

Table 4 above shows larger coefficients closer to the lake for both non-organized violence – protests and riots – and organized violence – mainly battles and violence against civilians.– Focusing on non-organized violence which better captures local conflict rather than the rise of large armed groups, one can see that conflict more than doubles in the lake's vicinity (150 km).[33] We will revisit these results in the QSM below.

[31] In our sample of 453 subdistricts the mean average monthly temperature in 1950-64 was already 27°C.

[32] Url: https://acleddata.com/. Last accessed: 03-28-2023.

[33] The non-organized violence results hold when restricting the analysis to the period 1997-2008 to exclude events related to Boko Haram and other Jihadist groups post-2009 (Appx. Table E.7). However, if the lake's shrinkage contributed to these groups arising, then we should not exclude the 2009-2019 period.

5. Model: Welfare Effects of the Shrinkage of Lake Chad

We develop a QSM to study the local and aggregate welfare effects of the shrinkage of the lake and simulate the effects of policies considering equity-efficiency trade-offs.

5.1. Quantitative Spatial Model (QSM)

There is a discrete set $\mathcal{N}$ of different locations i (453 subdistricts across four countries) and workers operate in four different sectors s: a fishing sector, an agricultural sector, a livestock sector, and an urban sector that captures both manufacturing and services.

Consumers have preferences in an upper nest for sectors and in a lower nest for varieties across locations as in Armington (1969). Consumers face spatial frictions in terms of iceberg trade costs. The utility function of worker ω in location j that migrates to location i is:

$$U_{ji\omega} = \epsilon_{ji\omega} d_{ji}^{-1} \left(\frac{T_i}{\delta}\right)^{\delta} \prod_s \left(\frac{C_{is}}{\alpha_s}\right)^{\alpha_s}. \tag{3}$$

T_i is land/housing. α_s is the expenditure share of goods s. δ is the expenditure share of land/housing, d_{ij} is an iceberg migration cost. ϵ_{ji} is an idiosyncratic shock that determines how people are willing to migrate to other areas in response to economic conditions. Finally, C_{is} is a CES aggregator across locations that takes a standard CES form where c_{jis} are the quantities of variety j and sector s produced in location j and consumed in location i:

$$C_{is} = \left(\sum_j c_{jis}^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}}. \tag{4}$$

In each location, a representative agent supplies one unit of labor and is the owner of a per capita unit of water and land. The indirect utility function is as follows:

$$V_i = \frac{u_i(w_i + r_i t_i + q_i \tilde{w}_i)}{P_i}$$

$P_i = \prod_s P_{is}^{\alpha_s}$ is the price index ($P_{is}^{1-\sigma} = \sum_j p_{jis}^{1-\sigma}$). w_i is the wage per efficiency unit. t_i=T_i/L_i and $\tilde{w}_i$=W_i/L_i is the number of land and water supply units per worker, respectively.

In each location-sector, a representative firm produces its own variety using Cobb-Douglas technology and faces iceberg trade costs to move goods across locations:

$$Y_{js} = A_{js} \left(\frac{L_{js}}{\beta_s}\right)^{\beta_s} \left(\frac{W_{js}}{\gamma_s}\right)^{\gamma_s} \left(\frac{T_{js}}{1-\beta_s-\gamma_s}\right)^{1-\beta_s-\gamma_s}. \tag{5}$$

A_{js} is total factor productivity, L_{js} is the number of efficiency units, W_{js} the amount of water units, and T_{js} the amount of land consumed. β_s is the output elasticity with respect to labor in sector s, γ_s the output elasticity with respect to water supply, and $1 - \beta_s - \gamma_s$ the output elasticity with respect to land. For the three primary sectors we assume constant returns to scale. For the urban sector, we assume an additional agglomeration force $A_{ju} = L_{ju}^{\mu}$, where μ captures external economies of scale.

Given this setting and assuming perfect competition, the price of the good produced in location j and sold in location i is equal to its marginal cost. Then,

$$p_{jis} = \frac{w_j^{\beta_s} q_j^{\gamma_s} r_j^{1-\beta_s-\gamma_s} \tau_{ji}}{A_{js}}.$$

$\tau \geq 1$ is the iceberg trade cost of moving goods from location j to location i, w_j is the wage per efficiency unit of labor in location j, q_j is the price of owater, and r_j is the price of one unit of land. We assume perfectly competitive input markets in which there are no frictions to reallocate inputs across sectors.[34] For the input supply, we assume perfectly inelastic supply curves in each one of the input markets. Given this setting, the market clearing condition for each one of the input markets in location j is given by:

$$w_j L_j = \sum_s \beta_s \sum_i \frac{p_{jis}^{1-\sigma}}{\sum_l p_{lis}^{1-\sigma}} \alpha_{is} X_i \tag{6}$$

$$q_j W_j = \sum_s \gamma_s \sum_i \frac{p_{jis}^{1-\sigma}}{\sum_l p_{lis}^{1-\sigma}} \alpha_{is} X_i \tag{7}$$

$$r_j T_j = \sum_s (1-\beta_s-\gamma_s) \sum_i \frac{p_{jis}^{1-\sigma}}{\sum_l p_{lis}^{1-\sigma}} \alpha_{is} X_i + \delta X_j \tag{8}$$

where X_i is the aggregate expenditure in location i. Imposing trade balances in the model, aggregate expenditure is then equal to aggregate income:

$$X_i = w_i L_i + q_i W_i + r_i T_i.$$

The idiosyncratic shock ϵ_{ij} is drawn from a Fréchet distribution with shape parameter η and location parameter u_i. η corresponds to the *migration elasticity.* When $\eta \to \infty$, workers are perfectly mobile across districts. With $\eta \to 1$, labor is fixed. Agents also face iceberg migration costs d_{ij}. From the properties of the Fréchet distribution, the share of people that migrate from location i to location j after a local economic shock is:

$$\lambda_{ij} = \frac{u_j V_j^{\eta} d_{ij}^{-\eta}}{\sum_l u_l V_l^{\eta} d_{il}^{-\eta}}.$$

The *amenity parameter* u_i captures how attractive a location is conditional on real income. We model it as u_i=$\bar{u}_i L_i^{-\lambda}$, with $\bar{u}_i$ the exogenous amenity value of location i and λ is the strength of the congestion force preventing the multiplicity of equilibria. Given risk-neutral agents "behind the veil of ignorance," expected utility in the economy is:

$$\bar{U} = \left(\sum_i \left(\sum_l u_l V_l^{\eta} d_{il}^{-\eta} \right) \right)^{\frac{1}{\eta}}.$$

Assuming that $\mu < \delta + \lambda + \frac{1}{\eta}$ (i.e., agglomeration forces are lower than dispersion forces),

[34]Following Lagakos and Waugh (2013) and Galle et al. (2021), this assumption could be relaxed by assuming an idiosyncratic shock drawn from an extreme value type distribution to move workers or other inputs across sectors. Relaxing the assumption would, if anything, increase the costs of the shock.

an equilibrium exists and it is unique (Allen et al., 2015). The general equilibrium of the model is described by the following vector of endogenous variables:

$$x = \{w_i, q_i, r_i, P_{is}, L_{is}, W_{is}, T_{is}, T_{iH}, L_i\},$$

given a set of exogenous parameters:

$$A = \{A_{js}, \bar{u}_i, \alpha_{is}, \beta_s, \gamma_s, \delta, \sigma_s, \mu, \tau_{ij}\}.$$

We use data c. 1963 to calibrate the model. Our quantification solves the model before and after the shrinkage of the lake. This is thus a static model that solves for the equilibrium in steady state. In our counterfactual, we then compare two steady states: The market allocation in 1963 vs. what would have happened if the lake had not shrunk.

Another option would have been to calibrate the model using ex-post data c. 2010 and assume that the lake recovers. However, some locational parameters must have changed endogenously due to the shock, and governments likely adopted place-based policies to help impacted communities cope with the shock. One contribution of this study is precisely the fact that we have data before the shock, even in the African context.

5.2. Calibration for 453 Subdistrict Locations

More details on the parameters and sources used are provided in Appx. Section E.

Productivity scale parameters and initial endowments. We calibrate total factor productivity measures for the agricultural and livestock sector using pixel-level information from FAO (2007). Their FGGD atlas estimates land suitability for rainfed crops, using maximizing crop and technology mix, as well as pasture.

Fishing output depends on the initial endowment of quality-adjusted water. Shore subdistricts have access to the full lake as country boundaries were not enforced on the lake's water (Couty and Duran, 1968). Yet, most of the open waters were located in the lake's Southern and Western areas, giving Cameroon and Nigeria easier access to productive waters. To obtain the productivity of each country's shore subdistricts, we rely on Couty and Duran (1968) who provide estimates on the contributions of each country to the total fish caught (tons) in the area in 1960-61. We then know the share of each country in the lake's total perimeter (shore) and area (surface). This allows us to estimate productivity ratios. For a given lake area, Cameroonian subdistricts and Nigerian subdistricts are overall 160% and 80% more productive whereas Nigerien subdistricts and Chadian subdistricts are 10% and 50% less productive, respectively.[35]

Coastal subdistricts have access to the sea area within 13 km from the coast (restricting Cameroonian fisher people to Cameroonian waters and Nigerian fisher people to Nigerian waters). Indeed, coastal fishing was dominated by small-craft fishing (NCMRED, 1968) and artisanal fishing units operated up to 13 km from the coast in Nigeria (Aderounmu, 1986). To obtain sea water supply in productivity-equivalent units

[35] In other words, Chad has a lot of shoreline and lake area for a given level of lake fish production.

of lake water supply, we use data on lake vs. sea fish production in both countries (sources: Chambre d'Agriculture (1965); NCMRED (1968)). Overall, seawater is 20% and 100% more productive than lake water in Cameroon and Nigeria, respectively.

For the urban sector, we calibrate its TFP by using the population size of the largest (5K+) city normalized by the total population in the subdistrict c. 1963.[36]

Expenditure shares. We exploit sources in the 1950s-1960s to reconstruct expenditure shares for each country c. 1963 (Appx. Section E; Appx. Table E.8). Ultimately, we choose 0.35 for farming, 0.10 for fishing, 0.10 for livestock, 0.35 for urban, and 0.10 for housing.

Input factor shares (Appx. Table E.9 reports the values used). For the agricultural sector, various studies find a land share (γ_s) of about 0.6, implying a labor share (β_s) of about 0.4.[37] For the livestock sector, Pellegrina (2022) estimate for Brazil a land share of 0.33 for agriculture and 0.53 for cattle, hence a difference of 0.2. In our case, the implied land share would be 0.6 + 0.2 = 0.8. Avila et al. (2010) obtain a land share of 0.55 for our four sample countries in 1961-80. However, it is unclear how they obtain their estimates. We thus consider a more intermediary land share of 0.7 (labor share = 0.3).[38]

There are no available estimates for the mostly artisanal fishing sector in Africa. However, fishing is likely as "land-intensive" as the livestock sector, except that "land" in this case is water. We thus use a water share of 0.7 (labor share = 0.3; land share = 0).

For the urban sector in a developed economy, Ahlfeldt et al. (2015) use a land share of 0.2 based on findings from Valentinyi and Herrendorf (2008). In developing economies, Tsivanidis (2019) and Khanna et al. (2020) obtain a labor share of 0.8 for Bogota and Medellin, respectively. We thus assume a land share of 0.2 (labor share = 0.8). We also ignore capital because our economies were not capital intensive c. 1963.[39]

Elasticities. Appx. Table E.10 shows the parameters and the values assigned to them.

We assume a migration elasticity of 3.0 in our African context. Morten and Oliveira (2023) recently obtained 4.5 using Brazilian data from 1980-2010 whereas Porcher (2020) found values of 2.92-3.12 for Brazil in 2000-2014. Likewise, Allen and Donaldson (2018) found values of 8.4, 6.8, and 5.6 for the U.S. in 1850, 1900 and 1950, respectively. West Africa had historically high levels of internal migration in the 1960s-2000s (Jedwab et al., 2017), which could justify a higher migration elasticity than found today for the more developed U.S. and European Economies ($\approx$ 2 as in Monte et al. (2018) and Caliendo et al. (2021)) or China due to the Hukou system (2.54 as in Tombe and Zhu (2019)).

[36] For Nigeria, we must rely on cities with 10K+ inhabitants c. 1960 (Africapolis, 2021).

[37] Weil and Wilde (2009) consider a land share of 0.57 for sub-Saharan Africa, whereas Chen et al. (2017) find a share of 0.58 for Malawi, which Restuccia and Santaeulalia-Llopis (2015) also assume for Ethiopia. Gollin and Udry (2021) find 0.61 for Tanzania and 0.53 for Uganda. Finally, using the estimates from Avila et al. (2010), we obtain an average share of 0.56 for our four sample countries in 1961-1980.

[38] Also note that we assume that the lake's water is not directly used as an input in both sectors.

[39] Capital is implicitly included in labor in our spatialized economy. Indeed, while land and water are spatially fixed, we assume that if there is any capital it is proportional to labor and "moves".

For the trade elasticity, we follow Simonovska and Waugh (2014) and Donaldson (2018) and use 4 (σ = 5) for the primary sectors. We use 1 (σ = 2) for the urban sector based on Boehm et al. (2020) who study the manufacturing sector. Many cities thus exist to provide non-homogenous local goods and services. For the congestion force, we use 0.32 from Desmet et al. (2018). For the agglomeration force, we use 0.10.[40]

Trade Costs: To calculate trade costs, we rely on the historical road quality database from Jedwab and Storeygard (2021) who digitized Michelin road maps produced between 1961 and 2014. We follow their methodology by constructing a grid of 0.1*0.1 degree ($\approx$ 11*11 km) cells and assigning to each cell a different travel time based on the best road quality in the cell c. 1963 (using the speeds they chose for each road quality; Appx. Table E.11).[41] Goods can then only be transported through 62 border cities as reported by the closest Michelin map to the year 1963. Finally, we also include a boat transportation mode through the lake (speed reported in Appx. Table E.11).

To transform the travel times between subdistricts into trade costs, we assume the same functional form as in Sotelo (2020) and Baldomero-Quintana (2021): $\tau_{ijs} = \exp(\delta * t_{ij})(1 + \text{tariff}_{ijs})$, where t_{ij} is the travel time between locations i and j, δ is the parameter that transforms travel times into trade costs, and tariff_{ijs} is a tariff of 20% if locations i and j are in different countries.[42] We estimate δ using information from: (i) the average price of "imported goods" for 48 Cameroonian cities in 1965 (source: Marguera (1975)); and (ii) the price of imported oil for 19 Nigerien cities and 4 semesters in 1962 (source: Commissariat Général au Plan (1965)). Since, within a country, the goods are relatively homogeneous and have the same point of entry, differences in local prices should disproportionately reflect differences in trade costs (Atkin and Donaldson, 2015). Given $p_{ijs} = \tau_{ijs} p_{js} (1 + \text{tariff}_{ijs}) = \exp(\delta t_{ij}) p_j (1 + \text{tariff}_{ijs})$, we estimate δ by running a regression within Cameroon and Niger relating the prices to travel times.[43] We obtain $\delta \approx 0.08$ (see Appx. Table E.12 for details), which is similar to what Allen and Arkolakis (2019) obtained for the U.S. (0.08) or Baldomero-Quintana (2021) for Colombia (0.13).

Migration Costs: We follow Hsiao (2022) and parametrize migration costs across locations as a function of Euclidean distance $\mu_{ij} = (1 + d_{ij})^{\phi}$ with an estimate of $\phi = 0.05$. We also include an additional penalty of 20% when crossing country borders.[44]

Finally, we invert the model and recover an amenity distribution for each location by matching the population in the data with the one from the model.[45]

[40] Combes and Gobillon (2015) and Ahlfeldt and Pietrostefani (2019) find $\approx$ 0.10 for poorer economies.

[41] They distinguish *highways*, *other paved roads*, *improved roads* (laterite or gravel), and *dirt roads*.

[42] For example, tariffs were on average 20% in Nigeria in 1962 (Govt of Nigeria, 1962).

[43] Since we estimate this regression within each country, we ignore tariffs.

[44] We use Euclidean distance rather than network distance since migration flows are likely shaped by historical economic and cultural links predating modern road networks. Hsiao (2022)'s parameter value is estimated for 1970-2010 Indonesia, another poor economic context with high internal migration rates.

[45] We recover the vector of amenities by perfectly matching the spatial distribution of the population implied by the model with the one from the data. Specifically, we solve for the real income measures, and

5.3. The Shock(s) in Our Model

We run a counterfactual that considers several sets of shocks due to the lake's drying:
Transport shock: Roads around the lake were of poor quality and evidence suggests it was cheaper to move goods by boat across the lake (Magrin et al., 2015). Trade costs increased when the lake shrunk as roads could not easily be built in former lake areas.
Fishing shock: Subdistricts that lost direct access to the lake experience a 100% decline in water supply. Subdistricts that still have access today experience a 95% loss in water supply and an additional productivity loss of 50% in the remaining (5%) lake area.[46]
Agriculture and livestock shocks: We consider several components:
- *Land supply:* Productivity increases in the subdistricts where the lake dried out. For the newly available land we assign to the affected pixels the value of the closest cell that is outside the lake and has a strictly positive value. However, this effect depends on property rights, land markets and infrastructure development in the former lake areas. We use satellite-based data on population patterns c. 2015 (source: Florczyk et al. (2019); resolution: $\approx$ 300*300 m) to obtain for each country a (area-weighted) average "development rate" *inside* the former lake areas relative to areas *outside* (in the same shore subdistricts). We obtain 7%, 15%, 4%, and 3% for Cameroon, Chad, Niger, and Nigeria, respectively.[47] The former lake areas remain largely underdeveloped today, due to incomplete property rights and land markets, lacking infrastructure, and security issues (Batello et al., 2004).[48] Also and as seen in Fig. 1, the emerged land consists of "disjoint marshy zones separated by dry land and [sandy] dunes" (Puzović et al., 2006). Finally, we weigh each subdistrict's suitability by the country's development rate.[49]
- *Irrigation:* Productivity is halved for pixels within a 20 km range from the lake's edge as we aim to capture the impact of losing access to irrigation.[50] Fuglie (2008), Fuglie and Rada (2013) and the World Bank find that irrigation can double productivity.[51]
- *Species extinction:* The lake's drying led to species extinction. While there were 200,000 Kuri cattle heads in 1972, there were only 10,000 heads left in 2002 (-95%).[52] Importantly,

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then we solve a system of equations such that the amenities match the model with the data.

[46] The lake's drying has been associated with higher ambient temperatures, lower dissolved oxygen, and the disappearance of spawning places and/or shelter for young fishes (Carmouze et al., 1983; Raji, 1993).

[47] More precisely, we compare the share of pixels with at least some population inside vs. outside. 100% would imply that the former lake areas are as "occupied" overall as the same subdistrict areas outside.

[48] They write: "[Though] there is great potential for increasing food production [...] production is still for household consumption and only a small portion of the cereals produced [...] reaches the marketplace."

[49] We use the country's development rate rather than a subdistrict-specific development rate as the latter is endogenous to local conditions, which we want to avoid in order to calibrate the model.

[50] We use 20 km since irrigation is small-scale in the area. Farming, for example, is done in "polder" depressions, i.e. interdunal valleys, around the lake (Evans and Mohieldeen, 2002; Luxereau et al., 2012). Lake water is brought there using traditional irrigation techniques (e.g., dense and deep networks of man-made furrows). When small dams and pumps are used, the water can be brought past the polders.

[51] See https://www.worldbank.org/en/topic/water-in-agriculture#1.

[52] For Mpofu and Rege (2002), the "importance of the Kuri lies [...] in its meat and milk production

the Kuri breed has a daily milk yield that is two times greater than other cattle breeds in the area (Santoze and Gicheha, 2018). From the website of the Animal Genetics Training Resource center,[53] we know which subdistricts had Kuri cattle. From various sources, we then obtain the number of cattle heads in the Lake Chad region c. 1963, thus the share of the Kuri breed in that total ($\approx 4\%$).[54] These numbers imply a cattle production loss of 7%. Since cattle accounted for 87% of total livestock units in the four countries in 1965 (FAO, 2021), the livestock productivity loss was 6% for each subdistrict with Kuris.

- *Local CC:* Productivity decreases within a 450km range of the lake due to CC caused by the shock. From Conte et al. (2021) we know the bell-shaped relationship between agricultural productivity and temperature.[55] Sultan et al. (2013) then use an agronomic model to examine for the Sahelian savanna the relation between the yields of the main food crops in the area – millet and sorghum – and rainfall.[56] Lastly, Seo and Mendelsohn (2008) use cross-sectional variation across livestock herders in 10 African countries to model the relation between livestock income and temperature as well as rainfall.[57]

- *Aquifer depletion:* Some of the lake's water used to seep through the ground into the Lake Chad transboundary aquifer (Isiorho and Matisof, 1990; Vaquero et al., 2021). Knowing the typical seepage rate as well as the geographical extent and initial size of the aquifer, we use our data on the evolution of the lake to obtain a groundwater loss (%) for each subdistrict. Assuming that 75% of water needs for livestock are met by groundwater (details below), we estimate a productivity loss (%) for each subdistrict.[58]

- *Transhumance:* For pastoralist communities, the lake was a feeding and watering zone during the dry season before the migration south to livestock markets in Cameroon and Nigeria. Following McGuirk and Nunn (2020), we use data from the ethnographic atlas of Murdock (1967) to classify some subdistricts as "transhumant pastoralist" (TP). For the TP subdistricts whose transhumance route historically went through the lake area,[59] we calculate by how much travel times to the (new) lake's edge must have increased using estimates of the distance typically covered per day by herds in Cameroon (Motta et al., 2018). Finally, since we know how much weight (output) is typically lost per day during the transhumance period (Amole et al., 2022), which was lengthened due to the shock, we can estimate a livestock productivity loss for each impacted subdistrict.

Amenity shocks: We consider several components:

potentials. The breed is so acclimatized to the environs of Lake Chad that it is unable to survive elsewhere"

[53] Url: http://agtr.ilri.cgiar.org/kuri, accessed 11-07-2021.

[54] See Appx. Section E for details on the sources used.

[55] Since their global estimation is cross-sectional, it should take into account agricultural adaptation.

[56] They obtain that yields should decrease by 0.67% for each percentage point of rainfall loss. They argue that agricultural adaptation is limited since these are the best crops for the harsh Sahelian conditions.

[57] They take into account adaptation from inter-species reallocation (cattle, goats, sheep, and chickens).

[58] According to the FAO's Global Information System on Water and Agriculture, only $\approx$10% of irrigation needs are met by groundwater across the four countries. We thus ignore the aquifer effect on agriculture.

[59] Sources include Carter and McLeroy (1968), Cabot et al. (1972), Haladou (1974) and Zieba et al. (2017).

- *Shoreline retreat:* We assume that shoreline communities (i.e., pixels within 10 km from the lake's edge) suffer a 50% amenity loss due to losing easy access to water.
- *Local CC:* For the 453 subdistricts, the exogenous amenity value that we obtain c. 1963 decreases by ≈12% for each additional °C.[60] Knowing how much temperatures increased due to the lake's drying, we estimate an amenity loss for each subdistrict.[61]
- *Aquifer depletion:* According to UNEP (2010), groundwater covers 75% of water needs in Africa, a number that we verify using data from the Demographic and Health Surveys in the four countries (which we also use for livestock). Knowing the groundwater loss of each subdistrict, we estimate an amenity loss from reduced access to drinking water.

Finally, note that we sum up the different components instead of interacting them. Indeed, we do not know how they interact. However, in our simulations, we obtain surprisingly similar aggregate losses when simultaneously including *all* shocks and subshocks in the simulation, or calculating losses considering each subshock *at a time* and then adding up the estimated losses (results not shown but available upon request).

5.4. Model Validation and Adaptation

As we focus on a natural experiment instead of future CC, we are able to validate the calibrated model using historical data for the initial (c. 1963) equilibrium and the reduced-form results for how we model the shock itself. There are four validation tests:
Initial sectoral GDP shares: For the four sectors in the four countries, Figure 5(a) below plots the model-predicted GDP shares within each country vs. the actual GDP shares c. 1963 (see Appx. Section E for the sources). Whether we use c. 1963 sectoral GDP values as weights or not, the coefficient of correlation is high at ≈ 0.80-0.85.[62] Likewise, we find very high correlation rates (> 0.95) if we compare the predicted shares and actual shares of each country-sector in the total GDP of the overall four-country economy.[63]
Distribution of Livestock Activities: Livestock is the only sector for which we can verify that our model predicts spatial production patterns. There does not exist data on total agricultural output at the subdistrict level c. 1963.[64] Likewise, we could not find spatialized data on fish caught. Lastly, we used city size as a proxy for urban productivity.

For the four countries we compare the model estimates of livestock GDP c. 1963 against (Appx. Section F1. for details and Appx. Fig. E.8-E.11 for the maps): (i) The actual distribution of livestock units c. 1963 which we obtain from administrative sources;[65]

[60] We include country fixed effects and control for latitude interacted with the country fixed effects since latitude is correlated with both temperature and historical development and infrastructure.

[61] We do not believe that 12% is unreasonable as temperatures were very high to start with in our region.

[62] The average absolute difference between the predicted shares and the actual shares is less than 5 pp for both Cameroon and Nigeria, less than 10 pp for Chad, and less than 15 pp for Niger. We do a better job for Cameroon and Nigeria which represent 89% of the four-country economy c. 1963 (Niger ≈ 7% only).

[63] The top three country-sectors c. 1963 are Nigeria-agriculture, Nigeria-urban, and Cameroon-urban.

[64] While data could be found for one or two crops in one country, data does not exist for all major crops.

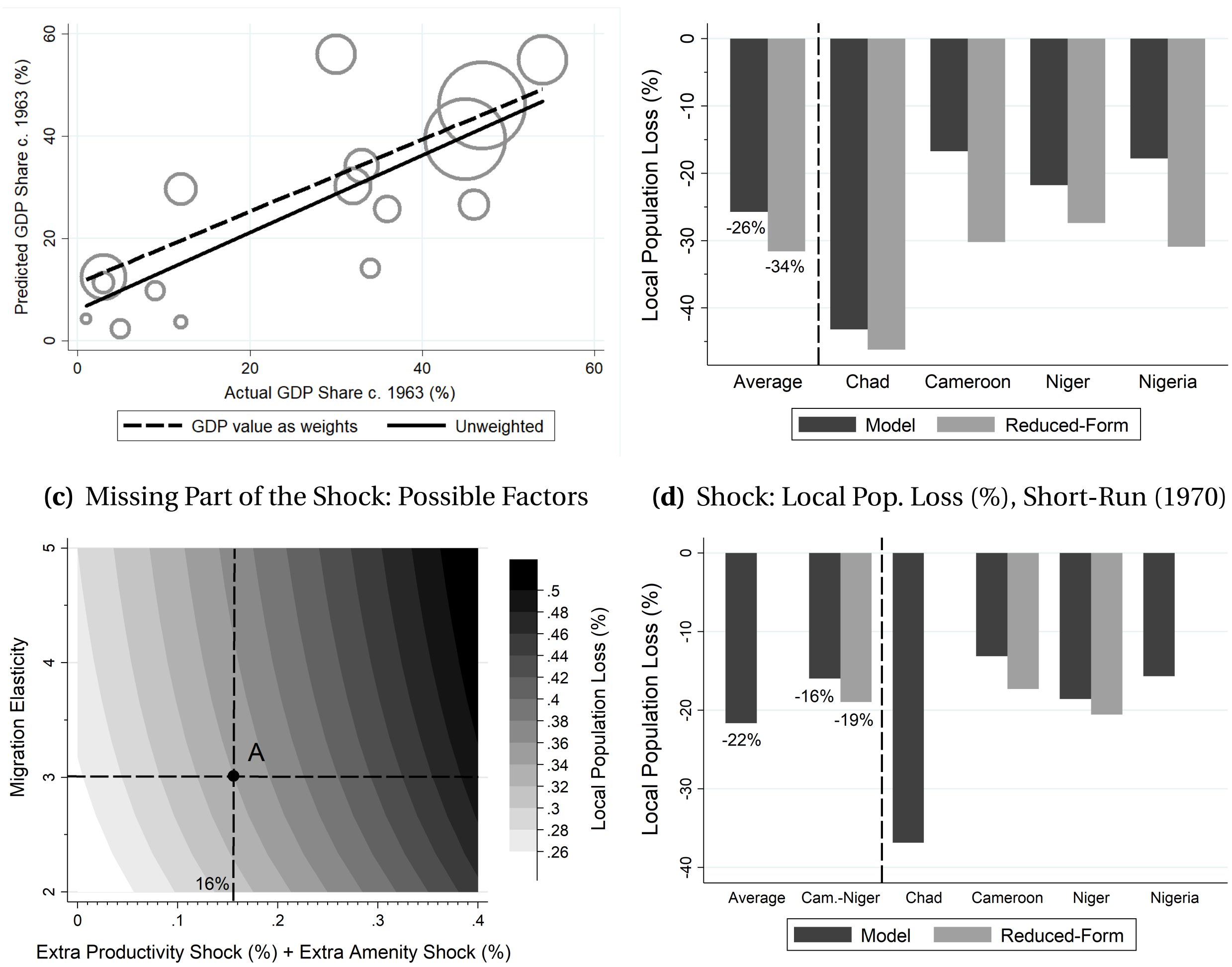
[65] Administrative sources usually report the number of livestock heads for each animal group (e.g, cattle and chicken). We convert each animal type into total livestock units using FAO (2003) conversion values.

(ii) The distribution of cattle heads c. 1963 as provided by Lunde and Lindtjørn (2013) who rely on historical cattle census data compiled by Deshler (1963); and (iii) The historical distribution of transhumant pastoralism (source: Murdock (1967), following the methodology of McGuirk and Nunn (2022)). Visually, we find spatial production patterns that are broadly consistent between the model and these other sources.[66]

Figure 5: Model Validation: Initial Equilibrium and the Shock

(a) Initial Equilibirum: GDP Shares (%) **(b)** Shock: Local Pop. Loss (%), Long-Run (2010)

(c) Missing Part of the Shock: Possible Factors **(d)** Shock: Local Pop. Loss (%), Short-Run (1970)



Notes: Subfig. (a) plots the initial model-predicted sectoral GDP shares within each country against the same shares in the data c. 1963. Subfig. (b) ((d)) plots the long-run (2010) (short-run (1970)) (relative) pop. loss (%) obtained with respect to log Euclidean dist. to the lake in the model against the same loss obtained in the data between the latest year available before 1963 and the closest year to 2010 (1970). We show the comparison for each country as well as on average across the four countries. Subfig. (c) shows the estimated pop. loss (%) for different combinations of the extra productivity and amenity shocks and the migration elasticity.

Distribution of Amenities: Across the four countries, the initial exogenous amenity values ($\bar{u}_i$) that we obtain when inverting the model (p. 18) are highly correlated with

[66] This is despite the fact that administrative sources over-represent livestock markets, i.e., where the livestock is sold instead of produced, as well as the dry season, when the spatial concentration of herders facilitates counting by governments, which over-represents wetter southern areas. This southern bias is accentuated in cattle-focused sources as cattle are bred in colder (more southern) latitudes than goats, sheep and camels. These issues prevent us from examining correlations more quantitatively.

measures of educational and health infrastructure c. 1963 (see Appx. Section F2. and Appx. Table E.13 for details). More precisely, we use historical sources to obtain data on (i) primary and secondary schools (including high schools) and universities; and (ii) hospitals, health centers, and dispensaries. The explanatory power of our regressions relating the exogenous amenity values to such measures is about 0.8 for Cameroon, 0.7 for Chad, 0.8 for Niger, and 0.75 for Nigeria. This gives us confidence that our amenity parameters indeed capture amenities and this also helps validate the calibrated model.

Local Population Loss (Long-Run): Across the four countries, the average long-run (c. 2010) population loss we obtained for subdistricts located closer to the former lake areas was -34 pp. In the model with distance-based migration costs and country fixed effects (N = 453), we obtain -26 pp – 75% of the reduced-form estimate–. Our model thus predicts well how people moved away from the lake due to the shock. See Fig. 5(b) above. Lastly, the model also predicts stronger effects for Chad than for other countries.

What could explain the remaining 25%? We likely did not model some adverse consequences of the lake's shrinkage. For example, we showed how conflict is more endemic in subdistricts located closer to the former lake areas. If conflict decreases productivity and/or lower amenities, as suggested by the literature – for example, see Khanna et al. (2020) in the case of Medellin –, then migration away from the former lake areas should increase. To examine this indirectly, we study what combinations of adding an extra productivity shock as well as an extra amenity shock and/or increasing the migration elasticity allow us to match the reduced-form estimate of local population loss.[67] More precisely, we assume that both total factor productivity and the amenity parameter decreases by x% in the lake region (within 450 km from the lake).[68]

With a migration elasticity of 3.0, $x \approx 16\%$ is enough to bridge the gap between the model and reduced-form estimates (see Fig. 5(c) above).[69] Thus, we do not miss much in the model to explain the data. It is likely that conflict and other unobserved mechanisms reduced productivity and amenities by such amounts. However, we ignore this in the rest of the analysis, which should lead to conservative estimates of aggregate losses.

Adaptation. The mean local population loss (%) in the data was 34% c. 2010. This is two decades after the lake stopped shrinking. Circa 1990, we find 36%, barely more. Thus, if there has been any adaptation during the 20 years or so after which agents had fully realized that the lake had permanently shrunk, it was likely limited ((34-36)/36*100 $\approx$ -5%). As such, we can confidently ignore adaptation in the rest of the analysis. In other words, adaptation being almost non-existent in our context, the long-run model estimates already implicitly include any local or national (or lack thereof) adaptation.

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[67] The migration elasticity indicates how people move in response to changes in economic condition. The larger the shock the likelier people may be willing to upend their lives, which increases the elasticity.

[68] Results hold assuming $2x$% for 150 km, x% for 150-300 km, and $x/2$% for 300-450 km (not shown).

[69] With an elasticity of 4.5 as obtained by Morten and Oliveira (2023) for Brazil 1980-2010, $x \approx 12\%$.

Short-Run. Lastly, we use the model only considering short-term (c. 1970) versions of the subshocks. As the lake had then shrunk by a fourth, we adjust most subshocks by a fourth. The subshocks that we do not adjust down – thus using the full shock value – are the shore-related subshocks. Indeed, shore retreating should have full effects regardless of whether the shore moves say 10 km away or 50 km away. This includes the transport, fishing, irrigation and amenity/shoreline retreat subshocks. For Cameroon and Niger ("Cam.-Niger"), the two countries with data c. 1970, we obtain -16 pp – 85% of the reduced-form estimate (-19 pp) – (see Fig. 5(d) above). We thus better explain the short-run, possibly consistent with increased poverty having feedback effects over time.

5.5. Aggregate Losses and their Spatial Distribution

We aggregate losses across subdistricts in two ways: (i) With the initial welfare weights whose loss estimates give more weight to locations in wealthier Nigeria; and (ii) Valuing the four countries "equally," in which case we use the initial welfare weights to compute each country's loss, and then report the average of the four country losses.

Results shown in Fig. 6 below consider our baseline scenario with *distance-based migration* costs ("Distance"; see Section 5.2. for details) as well as: (i) *Free migration* across all locations; (ii) *Cameroon-Chad-Niger (CCN) migration*: The residents of these three former French colonies do not move to Nigeria, a former British colony, perhaps due to linguistic differences. The residents of Nigeria only move to other locations in Nigeria; (iii) *Migration within countries*: Borders are closed; and (iv) *Migration within regions*: Residents only move to other locations in the same region;[70]

We find significant losses rather than gains, suggesting that the positive effects from increased land supply were largely outweighed by the other (negative) effects. We then tend to find that the higher the migration costs, the higher the losses, with losses $\approx$ 5.7-8.0% depending on the migration scenario and weighting scheme (columns 1-2). When some locations become less productive in some sectors, production in these sectors is less impacted if the labor can move to other locations where production can take place.

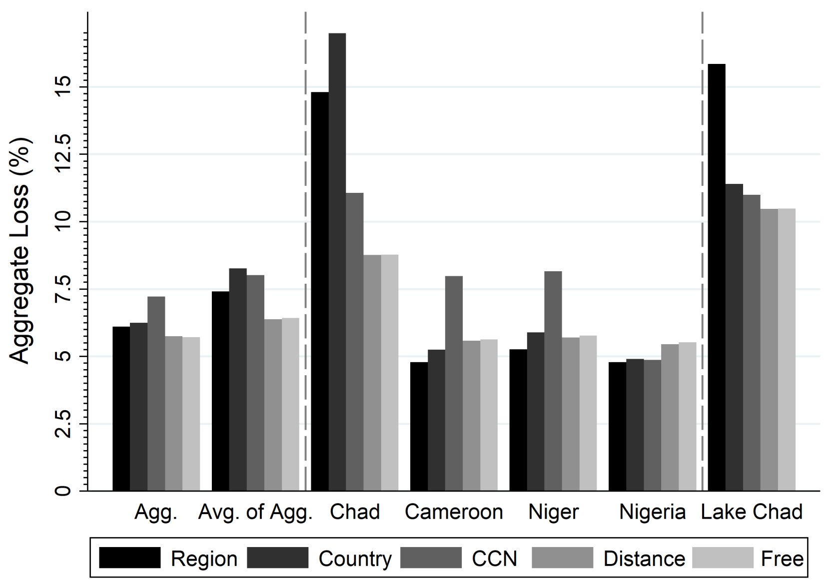
However, this is less true when not considering countries equally ("Agg.") than when treating them equally ("Avg. of Agg."). Indeed, with lower migration costs more residents move to (higher weighted) Nigeria. Losses are then the highest with migration limited to CCN (in the case of Agg) or countries (Avg of Agg). The higher losses with CCN/country migration than in the case of regional migration are mostly due to negative congestion effects from migration. Indeed, we verify that migrants flock to few locations in CCN (most often wealthier Cameroon) or their own countries, which increases congestion.

While migration typically helps reduce losses in the literature on natural disasters, losses remain high in our distance and free migration scenario, at 5.7-6.4%, which is still

[70] We use broad regional boundaries c. 1963. There are 6, 9, 7, and 4 such regions in Cameroon (pre-1960), Chad (1955), Niger (1964), and Nigeria (1961), respectively. These regions correspond to regional labor markets whose subdistricts likely share common ethnolinguistic and religious traits.

80-85% of the maximal loss across all scenarios. Thus, migration within the region has a limited mitigating impact in our context. CC literature has found that migration can substantially reduce future CC impacts. Desmet et al. (2021) find that sea level change may generate global losses of 4.5% which could be reduced to 0.11% with free migration. Conte (2021) finds that free migration changes future CC losses from 1% to a positive gain of 3.65%.[71] An explanation for our result is that in our context, the most affected regions are also among the poorest ones, with a lower weight in the aggregate welfare function. In contrast, in the case of CC, both poor and wealthier areas within Africa are affected equally. Also, unlike a comparison of all the countries of the world or the whole of Africa, these four countries share relatively similar economic conditions.

Figure 6: Aggregate Losses, Different Groupings of Countries and Subdistricts



Notes: Agg: We use initial welfare weights. *Avg of agg:* We use initial welfare weights for each country and we then report the average of the four country losses. Lake Chad: Aggregate losses (using initial welfare weights) for subdistricts within 450 km of Lake Chad.

Next, aggregate losses are driven by Chad, the most exposed country in terms of lake shoreline (Fig. 3). Furthermore, with Chad being the least urbanized country along with Niger, its economy is more exposed to the mostly-rural lake shock. For Chad, losses clearly decline as migration costs decrease and it sends its migrants to other countries. The other countries experience similar losses overall, with losses peaking as expected for Cameroon and Niger in the CCN scenario, and Nigeria in the free migration scenario.

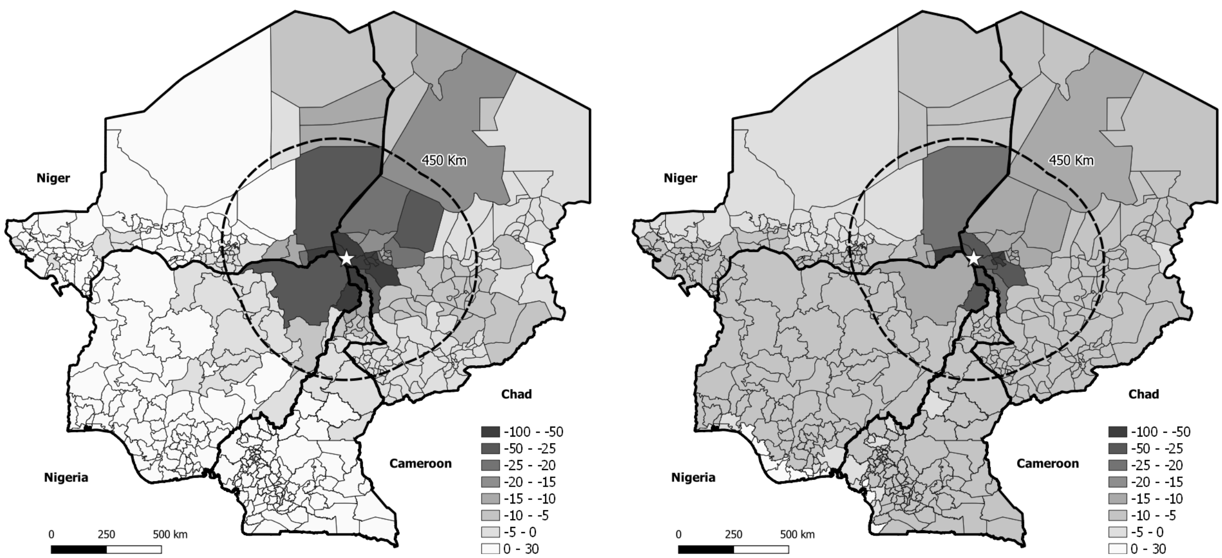
The last column shows losses for the Lake Chad Region (LCR), defined as subdistricts within 450 km of the lake (see Figure 7 below). Losses are much higher than in the aggregate, at 10-15%, implying that spatial inequality increases. Lower migration costs unambiguously help the region as the shock can be spread out across more areas.

[71] Both of these papers aggregate welfare using a weighted average of real income instead of using the utility function from section 5.1. that assumes risk-neutral individuals

Consistently, Fig. 7 below shows the long-run changes in population and real income + amenities as predicted by the baseline model (with distance-based migration costs). The LCR and many subdistricts located outside the LCR (especially in Chad) register population losses (subfig. (a)). Indeed, almost all these places experience significant losses in terms of real income (due to nominal incomes and/or prices) and/or amenities (subfig. (b)), and population as it reallocates to less impacted locations.[72] To summarize, though the LCR occupies only 20% of the area and comprised only 13% of the population c. 1963, the shock was large enough to affect the economy by $\approx$ 6%.

Figure 7: Long-Run Changes Predicted by the Model

(a) Population (%) **(b)** Real Income + Amenities (%)



5.6. Using the Validated Model to Study Past CC and Future CC

Having used the lake shock to validate our calibrated model, we can use the same model to explore the effects of past and future CC when only considering temperature and rainfall changes. This also helps us benchmark and analyze losses due to the lake shock.
Past CC. We use our temperature and rainfall data (Appx. Section B) to obtain their long-run change between 1960 and 2010 when removing the local CC effects from Lake Chad. On average, temperatures increased by 1.0°C and rainfall decreased by 13% (80 mm).

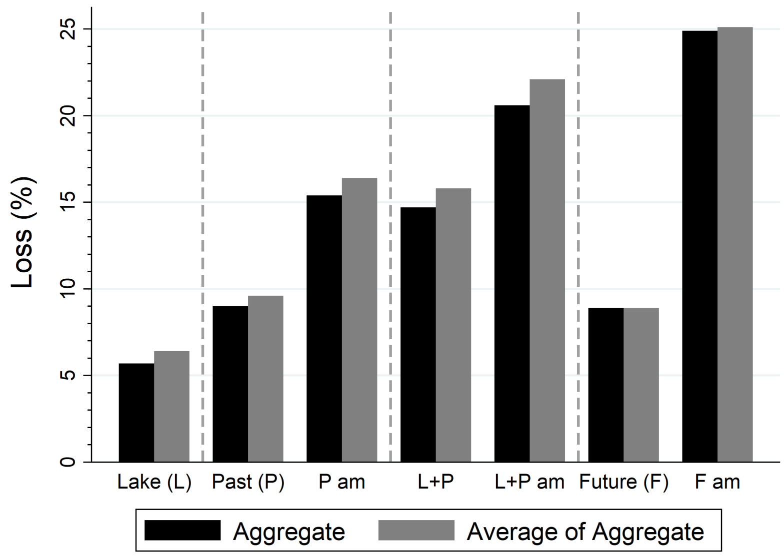
As seen in Fig. 8 below, losses reach $\approx$ 10% when not including the amenity loss from higher temperatures ("Past (P)"), and $>$ 15% when including it ("P am"). The lake shock's loss ("Lake (L)") thus amounts to two-thirds or two-fifths of the past CC loss depending on whether amenity losses are included. Since we found very limited adaptation for the lake shock ($\approx$ 5%), we can plausibly ignore possible adaptation for past CC.[73]

[72] Note that congestion forces work through the price of land/housing and amenities.

[73] We report the baseline results with distance-based migration costs and the initial welfare weights (not treating countries equally). Results are very similar when using the welfare weights to compute each

Since the past CC shock is more uniform spatially than the regional lake shock (i.e., many subdistricts experienced similar changes in their climate since 1960), lowering migration costs has a smaller impact in the case of past CC. Indeed, the loss with free migration is $\approx$ 90% of the maximal loss across all scenarios (vs. 75% for the lake shock).

Figure 8: Lake Shock Losses vs. Pure Climate Change Losses



Notes: Aggregate: We use initial welfare weights. *Average of aggregate:* We use initial welfare weights for each country and we then report the average of the four country losses. "am": We include the amenity losses from higher temperatures.

Adding up the lake and past CC shocks, we get about 15% without the amenity loss ("L+P") and 20% with it ("L+P am"). If we add up the individual lake shock losses and past CC losses, we get similar losses overall, which suggests a fair amount of separability.

Future CC. For each subdistrict, we obtain from the Climate Change Knowledge Portal of the World Bank temperature and rainfall changes between 2010 and 2060 (we consider 50 years as we use 50 years for the lake shock and past CC).[74] We use the CMIP6 (mean projections) collection and examine the intermediate SSP5-RCP4.5 scenario.[75] We get mean temperature increases of 1.6°C and mean rainfall increase of 11% (45 mm). CMIP6 projections indeed show that rainfall may increase over West Africa.

2010 being the start year of the period of study, we calibrate the model by adapting the parameter values of Section 5.2. to 2010 conditions. We use the small lake, city sizes c. 2010, expenditure shares c. 2010 (see Appx. Section E for details), trade costs based on c. 2010 roads, population levels c. 2010, and invert the model to obtain amenities.

We obtain 9% when not including the amenity loss from higher temperatures and 25% when including it (Fig. 8).[76] The lake shock's loss amounts to two-thirds or one-fourth of the future CC loss depending on whether possible amenity losses are included.

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country's loss and then taking the average across the four countries (treating countries equally).

[74] Url: https://climateknowledgeportal.worldbank.org/. Last accessed 08-24-2023.

[75] In this scenario, CO2 emissions start declining by 2045 to reach half of their levels of 2050 by 2100.

[76] We get 13% and 35% with the most pessimistic SSP5-RCP8.5 scenario ("fossil-fueled development").

Lastly, since the future CC shock will be far more spatially uniform than the regional lake shock, lowering migration costs has almost no impact in the case of future CC (the loss with free migration exceeds 95% of the maximal loss across all scenarios).

The global drying of lakes is one aspect of CC, much like coastal flooding. Yet, the losses that we obtain in our African context appear substantial compared to the general CC effects from rising temperatures and declining rainfall. Since drying lakes are more localized shocks, one may wonder to what extent place-based policies may alleviate their aggregate effects. We investigate this question in the last section.

5.7. Model Extensions

We consider several extensions of the baseline model with distance-based migration:

Post-Shock Expenditure Shares. The baseline uses pre-shock shares which agents may adjust following the shock (i.e., if the price of fish increases, people will likely consume less fish). Circa 2010, expenditure shares are lower for both fishing and livestock (5% vs. 10% c. 1963) and higher for agriculture (45% vs. 35%).[77] Losses are lower but remain high, at $\approx$ 4-5% vs. 6% in the baseline (see Fig. 9 below). However, shares may differ today due to changes unrelated to the lake. Additionally, if shares changed due to the shock, the question remains whether no loss should be considered when communities, who had for generations relied on certain products for their nutrition, e.g., lake fishes for lake communities, adjust their consumption basket in the face of CC. Simply using ex-post expenditure shares may then under-estimate cultural and economic losses.

CES Utility Function. With nested CES preferences, expenditure shares also respond to the shock. We invert the model to recover taste-shifter parameters matching the expenditure shares and assume an elasticity of substitution across sectors equal to 2 for the upper nest utility function (source: Edmond et al. (2015); see Appx. Section F3.1. for details on the model), losses are lower but remain high, at $\approx$ 4.5-5.0% (see Fig. 9 below).

Non-Homothetic Preferences. Following the model of Comin et al. (2021), expenditure shares respond to price changes and also to income changes depending on a parameter that can vary across sectors (see Appx. Section F3.2. for details).[78] In our case, primary goods are necessity goods, meaning that as income increases, the expenditure share decreases. In contrast, the urban good is a luxury good; as income increases, the expenditure share also increases. Losses then increase to $\approx$ 7-8% (see Fig. 9 below).

Trade Elasticities. The baseline assumes moderate substitutability between lake fishes and sea fishes (the trade elasticity is 4 for the primary sectors). This may lead us to underestimate losses. Losses increase to $\approx$ 8.0-8.5% if we make the two types of fish less substitutable by lowering the trade elasticity of fishing to 1, the value for the urban sector (see Fig. 9; "Trad Fish"). Losses slightly increase if we sequentially lower to 1 the

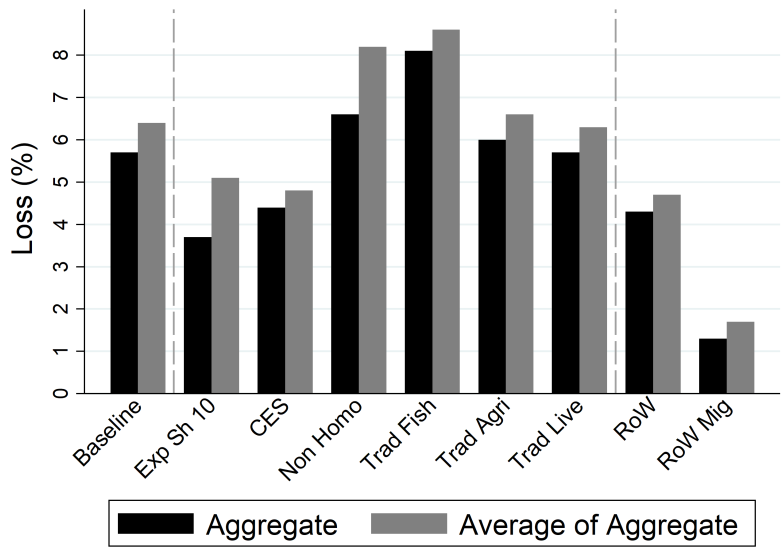
[77] See Appx. Section E for details on the sources.

[78] We use the parameters from Conte (2021) and Nath (2022) who also study the consequences of CC.

trade elasticity of the other primary sectors (Fig. 9; "Trad Agri" or "Trad Live").

Thus, using ex-post expenditure shares or nested CES preferences slightly lowers losses, and making preferences non-homothetic or reducing trade elasticities slightly increases losses. The truth likely lies in-between, which is where our baseline estimates are situated. Therefore, we believe that our baseline estimates are reasonable.

Figure 9: Long-Run Losses with Various Model Extensions



Notes: Aggregate: We use initial welfare weights. *Average of aggregate:* We use initial welfare weights for each country and then report the average of the four countries' losses. See text for details on each robustness check.

Including the Rest of the World (RoW). We add the RoW as a 454th location (see Appx. Section F3.3. for details).[79] If we only allow for costly trade with the RoW, losses are lower but remain high, at about 4.0-4.5% (see Fig. 9). This is assuming that the cost of distance is about three times lower for ships than by road within our region.[80] If we additionally allow for costly migration to the RoW, losses are lower, at $\approx 1.5\%$ (Fig. 9).[81] However, since international borders are currently mostly "closed," despite CC already severely impacting many locations on earth, it may not be realistic to allow for international migration. We thus believe that our baseline estimates remain reasonable.

6. Policy Results

Land Suitability in the Former Lake Areas. The first set of policies consists of establishing clear property rights, facilitating the creation of land markets, ensuring safety, and providing a minimal level of infrastructure to develop the land that became

[79]Data from FAO (2007) gives us the land supply and farming and livestock suitability of the RoW. Data on territorial waters gives us water supply in the RoW. Urbanization data gives us the relative urban productivity of the RoW. Distance to Europe's largest port –Rotterdam– is used for trade/migration costs.

[80]Within our region, we use 80 kph, 60 kph, 40 kph and 12 kph for highways, paved roads, improved roads, and dirt roads, respectively. Cargo ships typically travel at a speed of 13-15 knots, or 24-28 kph. We see these results as possibly overestimating the minimizing impact of trade with the RoW.

[81]We use the same costs of distance and crossing borders as within the four-country region.

available. We simulate the effects of raising the development rate – the ratio of the share of land that is occupied "inside" the former lake areas to the share of land that is occupied "outside" (in the same subdistricts with lake areas) – to 50%, 100%, 200% or even 300%.[82] Table 5 below shows how losses decrease when doing so.[83] In the baseline, with distance-based migration and where crop/pastoral suitability in the former lake areas is proxied by crop/pastoral suitability in the closest non-lake cell with a non-zero value ("Closest Cell"), the impact is limited. The 5.7% loss is at most reduced by 0.4 pp.

Table 5: Loss Reduction when Facilitating Land Development in the Former Lake Areas

Assigned Land Quality	Development	Distance	Regional	Country	CCN	Free
p75 of Country	Baseline	0.0	0.0	0.0	0.0	0.0
Max of Country	Baseline	0.1	0.1	0.1	0.1	0.1
Max of Region	Baseline	0.1	0.1	0.1	0.1	0.1
Closest Cell	50%	0.1	0.1	0.1	0.0	0.1
p75 of Country	50%	0.2	0.2	0.2	0.1	0.2
Max of Country	50%	0.6	0.6	0.5	0.3	0.6
Max of Region	50%	0.6	0.7	0.6	0.4	0.6
Closest Cell	100%	0.1	0.1	0.1	0.1	0.1
p75 of Country	100%	0.4	0.4	0.3	0.2	0.4
Max of Country	100%	1.1	1.1	0.9	0.6	1.1
Max of Region	100%	1.2	1.3	1.1	0.7	1.2
Closest Cell	200%	0.3	0.3	0.2	0.2	0.3
p75 of Country	200%	0.7	0.7	0.6	0.5	0.7
Max of Country	200%	2.0	2.2	1.8	1.2	2.0
Max of Region	200%	2.3	2.4	2.1	1.4	2.3
Closest Cell	300%	0.4	0.4	0.3	0.2	0.4
p75 of Country	300%	1.1	1.1	1.0	0.7	1.1
Max of Country	300%	2.9	3.1	2.6	1.7	2.9
Max of Region	300%	3.2	3.4	2.9	2.0	3.3

Notes: This table shows how lower negative aggregate losses could depend on: (i) the assigned land quality in the former lake areas; and (ii) the development rate used for the former lake areas, i.e., the ratio of the share of land that is occupied "inside" the former lake areas to the share of land that is occupied "outside" (in the same subdistricts containing the former lake areas).

This result is likely due to the low quality of the land surrounding the lake. As robustness checks, we assign instead the land quality of: (i) the 75th percentile value in the country; (ii) the maximal value in the country; and (iii) the maximal value in the region.[84] As seen in Table 5, one would need the development rate and suitability to be very high (max of country or region) to see meaningful mitigating impacts. However, the largest mitigating effect with a development rate of 100% is 1.2 pp, which is only 20% of the 5.7 pp loss. One would need land development in the former lake areas to far exceed today's development level just outside lake areas to see strong effects (e.g., a loss reduction of 3.2 pp with the highest suitability values in the region and development

[82] In the baseline, we used the data-based values of 3-15% depending on the country.

[83] We use the initial welfare weights for the table. Results are similar when using the weights to obtain each country's loss and then averaging the losses across the four countries (not shown).

[84] Across the four countries, the maximal suitability values are 77-97% for crops and 17-88% for livestock (adjusted for the tse-tse fly). In comparison, the mean, 75th percentile and 90th percentile values of suitability in the U.S. are 47%, 79% and 93% for crops, and 38%, 73% and 87% for livestock, respectively.

= 300%). Interestingly, the results are not too sensitive to migration costs. Across the different migration scenarios, only the absolute differences between the maximal and minimal values in the loss increase with the assigned land quality and development rate.

The small land supply effect might also be a specific feature of our study, because Lake Chad was in a mostly arid region. To some extent, this made the lake more crucial to local populations. In other contexts, where lakes are in cooler climates and surrounded by better land overall, the land supply effect could be larger. However, increasing disappearance of lakes is not a phenomenon that we want to encourage to obtain more land in poor countries because of the fact that lakes have positive effects on the local climate (i.e., raising land productivity in the environs).

We now simulate different policies related to: (i) the *absorption capacity* of rural locations and cities; (ii) *road construction*; (iii) *trade liberalization*; and (iv) *international migration*. To calculate how much these policies reduce the negative effects of the lake's shrinkage, we must ignore the positive individual effect of the policy itself. To do so, we simulate the policy's impact two times, once before the lake's shrinkage, and again after it. Next, we obtain the difference in the impact between the two, which captures how differentially important the policy is in the post-shock economy.

Col. (1) of Table 6 below shows how much the aggregate loss is reduced in percentage points when using our baseline distance-based migration scenario. Col. (2) shows the same differential effects when migration is restricted to broad regions. Col. (3) considers the Lake Chad region (LCR) only (i.e., subdistricts within 450 km from Lake Chad). Since results are similar when weighting the welfare of each country equally instead, we only report the results with the aggregate effects across the four countries, which over-represents wealthier Nigeria (not shown but available upon request).

Col. (4) shows how the absolute reduction in the aggregate loss compares to the loss that we estimated in the baseline, i.e. 5.7%. The loss reduction is then expressed in percentage terms. Col. (5) does the same for the LCR, where the loss was 10.5%. Finally, col. (6) shows the ratio of (5) and (4), i.e. to what extent the policy has a larger or smaller proportional effect in the LCR relative to the whole region. A social planner concerned about spatial inequality may want to consider the LCR's losses specifically.

Absorption Capacity. Rows 1-4 of Table 6 below show the results when we reduce the congestion externality, which affects all locations, and increase the agglomeration externality, which only affects the urban sector. Although the government cannot directly affect these parameters, we want to simulate policies that raise the capacity of non-directly impacted (non-LCR) locations to absorb migrants from the LCR.

If we reduce the congestion externality from -0.32 to -0.20 (37% reduction; row 1), the loss decreases by 0.9 pp ((1)), or 16% of the baseline loss ((4)). Reducing the congestion externality in rural locations only (row 2) or urban locations only (row 3), we find similar effects that seem to account for about half of the overall effects when reducing the congestion externality across all locations (0.5 and 0.4, respectively).[85] The effects are then proportionally weaker for the LCR ((4)-(6)). They are then stronger in the regional migration scenario ((2) vs. (1)). Indeed, with lake refugees not being able to "spread out" across more territory throughout the region, congestion effects increase, which raises losses. Increasing the absorption capacity of non-LCR locations should thus help integrate lake refugees economically, which reduces losses in the aggregate.

Table 6: Loss Reduction from Various Policies

Reduction in the Loss:	Percentage Points			% of Total Loss		
	(1)	(2)	(3)	(4)	(5)	(6)
Policy:	Aggregate	Region Mig	LCR	Aggregate	LCR	LCR/Agg
1. Congestion ext. -0.20 (-0.32 before)	0.9	2.3	0.4	0.16	0.04	0.2
2. Congestion ext. -0.20, Rural only	0.5	1.3	0.2	0.09	0.02	0.2
3. Congestion ext. -0.20, Cities only	0.4	1.2	0.3	0.07	0.03	0.4
4. Agglomeration ext. 0.2 (0.1 before)	0.0	0.2	-0.1	0.00	-0.01	1.0
5. Paving roads around Lake Chad	0.1	0.1	0.2	0.02	0.02	1.1
6. Paving roads lake $\rightarrow$ largest city	0.2	0.1	0.3	0.03	0.03	0.8
7. Paving roads largest city $\rightarrow$ lake	0.3	0.2	0.4	0.05	0.04	0.7
8. Region tariffs 10% (20% before)	-0.1	-0.1	-0.1	-0.02	-0.01	0.5
9. RoW tariffs 10% (20% before)	0.1	0.1	0.2	0.02	0.02	1.1
10. RoW cost distance 0.02 (0.03 before)	1.6	1.5	2.5	0.28	0.24	0.9
11. RoW adding international migration	3.0	0.0	2.8	0.52	0.27	0.5

Notes: (1)-(3): We report the absolute reduction (pp) in the percentage loss from the lake's drying. (4)-(6): The reduction is expressed as a percentage of the total loss, which is 5.7% in the aggregate and 10.5% in the Lake Chad region (LCR; subdistricts located within 450 km from the lake). We use distance-based migration except in (2) where we consider regional migration only.

Lastly, increasing the agglomeration force in the urban sector (from 0.10 to 0.20; row 4)) does not substantially mitigate the adverse effects of the shock. We find that the countries' urban share increases little as a result of the shock.[86] Agglomeration effects are thus not that different in the economy before the shock hits vs. after it does. However, we see a slightly larger effect of the agglomeration policy when migration is restricted to regions only ((2)). If rural migrants cannot move to other rural areas in the rest of the country or across the four countries, they may have move to urban areas in their own region. Then the agglomeration policy becomes slightly more consequential.

Road Building. In rows 5-7, we recalculate the travel times/trade costs between the various subdistricts after the government paves roads that were unpaved before. We first simulate a policy that paves the (as of 1963) unpaved ring road around the lake (row 5).[87] 83 cells are paved in total, including 45 in Chad, 19 in Nigeria, 10 in Niger, and

[85] We define as "urban" any subdistricts that already had cities c. 1963.

[86] Including non-homothetic preferences in the model might have even reduced the urbanization rate.

[87] To define the ring road, we study the 1963 Michelin map. The map indicates if a road is "transcontinental or important." We use this information to select some road segments, i.e. cells. For the remaining road segments, we select the cells whose paving minimizes the travel time around the lake.

9 in Cameroon. 83 cells to be paved is thus the budget that we use for our simulations. Note that it corresponds to 8% of the total paved network as of 1963. As seen in row 5, the differential effect is small (0.1 in (1)), lowering the overall loss by only 2% ((4)).

We thus try a second policy which uses the same budget but instead paves the unpaved cells of the fastest road from the lake to the country's largest city as of 1963 (row 6).[88] The differential effect slightly increases (0.2 in (1)). Lastly, we pave the unpaved cells of the fastest road from the country's largest city to the lake (row 7). Since the largest cities typically already had paved roads around them c. 1963, this leads us in some cases to pave roads located in more intermediary regions between the largest city and the lake. The differential effect further increases but remains small (0.3 in (1)).

Of course, with a larger road budget the effects would also be larger. What may be more interesting is the fact that aggregate losses are reduced more with roads being paved in more central areas than the LCR. With the LCR becoming less attractive with the lake shock, and central areas having to offset congestion effects from lake refugees (and benefiting from larger agglomeration economies due to higher economic density), paving roads in non-LCR locations has a stronger impact. Consistently, the aggregate effects are slightly higher when migration is not restricted to regions ((1) vs. (2)).

Results may however differ if focusing on spatial inequality. In proportional terms, the LCR benefits more from paving the lake's ring road (LCR/Agg ratio > 1 in col. (6) of row 5). Yet, in absolute terms, the LCR benefits more from roads being paved in more central areas (row 7 vs. row 5 in col. (5)). Therefore, leaving aside inequality and only focusing on the LCR's welfare, it might be better to pave roads *away* from the LCR.

Lastly, we find similar results if we allocate the same budget of $83 \div 4 \approx 21$ cells to each country (not shown). Since Chad has more lake shoreline than the other countries, it would make sense that Chad receives more road funding from, say, the international community. But the international community may also want to treat each country equally, in which case each country would have to receive the same budget.

Trade. Row 8 shows that lowering tariffs between the four countries from 20% to 10% does not reduce losses. Unlike a comparison of all the countries of the world or the whole of Africa, these four economies have relatively similar endowments. Consistently, row 9 shows slightly stronger effects of reducing tariffs with the rest of the world (RoW). However, the effects remain limited due to high trade costs with the RoW. In row 9, we lower by a third the parameter that converts distance to the RoW into trade costs to the RoW. This makes the cost of distance four times lower for shipping from/to the RoW than for roads within the region (instead of about three times lower in the baseline). Losses are now reduced by 1.6 pp, or 28% of the overall loss. These large effects show how investments in sea transportation technology might help lower CC-related losses in poor economies. However, the aggregate loss still remains large, at 5.7 - 1.6 = 4.1%.

[88] We also prioritize roads indicated as transcontinental or important in the 1963 Michelin map.

International Migration. Row 11 shows that aggregate losses are reduced by up to 3 pp ((1)) – half of the total loss ((4)) – when allowing international migration (using distance-based migration costs).[89] Non-LCR areas benefit more than LCR areas since they are the ones receiving lake migrants. With the RoW acting as a "safety valve," the non-LCR also sends migrants to other locations. However, we discussed in Section 5.7. how unlikely it is that richer countries would welcome CC migrants from poor economies.

To summarize, the potential of domestic and international policies to reduce aggregate and local (LCR) CC-related losses in poor and little diversified agrarian economies appears limited. Focusing on more realistic policies and not including costs, aggregate and local losses are reduced by a fourth or less (cols. (4)-(5) of rows 1-10).

Transaqua. We perform a simple cost-benefit analysis to understand the effects of the Transaqua project that proposes the construction of a 2,400-km canal aimed at diverting enough water from the Congo River Basin in the Democratic Republic of the Congo to replenish Lake Chad (Appx. Fig. E.7 shows the project). The cost of the project is estimated to be US$50 billion (Sayan et al., 2020; The Conversation, 2021), one tenth of the region's GDP in 2019. Using today's GDP numbers and the aggregate losses we find, the total benefit of the project would be about US$33 billion, implying that it would only cover $\approx$ 65% of the total cost. Were we to use the four countries' (much lower) GDP numbers in 1965, the Transaqua project would create an even smaller benefit.

7. Conclusion

Despite an extensive literature on the current and future economic effects of CC, the past economic effects of CC as defined by the IPCC, and specifically lakes diminishing in size, have not been widely investigated to our knowledge. We focused on Lake Chad, historically the 11th largest lake in the world which lost 90% of its surface area between 1963 and 1990. For Cameroon, Chad, Niger, and Nigeria – 25% of sub-Saharan Africa's population today – we constructed a novel data set tracking population patterns at a fine spatial level from the 1940s to the 2010s. We then exploited a panel difference-in-difference strategy to estimate the effects of the lake's shrinkage on nearby communities. We found slower growth in the proximity of the lake, despite the increased land supply there. We did not find evidence for population recovery in the long run.

We then used a calibrated quantitative spatial model to show that the shrinkage of the lake had large negative local and aggregate effects, and examined the effects of policies related to migration, trade, land use, roads, and cities. While our work cannot fully answer the question of how governments should respond to CC, and shrinking lakes specifically, our results suggest that CC-related natural disasters could have permanent negative effects on poor agrarian economies, especially in Africa.

[89] In comparison, in the baseline model without the RoW, the aggregate loss reduction between the maximal and minimal loss across the five different domestic migration scenarios was 20%.

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WEB APPENDIX NOT FOR PUBLICATION

A Shrinkage of Lakes and Drying of Rivers Across the World

Other examples of drying lakes include: (i) The Dead Sea, that is drying due to CC;[90] (ii) Qinghai Lake, China's largest lake, during most of the 20th century (Dong et al., 2018). The lake "is not only a natural barrier preventing the spread of desertification from the west to the east, but also has a significant influence on climate in the Yellow River catchment;" (iii) Poyang Lake in China, due to repeated droughts as well as the Three Gorges Dam upriver on the Yangtze River;[91] (iv) Lake Poopo in Bolivia, due to CC;[92] and (v) Hamun Lake in Afghanistan and Iran, due to extreme droughts;[93] Other examples include Lop Nur in Mongolia, Lake Chapala in Mexico, the Dead Sea, Lake Ebinur in China and Lake Faguibine in Mali, almost always due to global CC.[94]

More US examples include: (i) Pyramid Lake in Nevada; (ii) Owens Lake, another Californian lake that is now a major source of dust pollution; (iii) Walker Lake in Nevada; and (iv) Mono Lake in California.[95] The shrinkage of Lake Mead in Nevada has alarmed the media.[96] Similar concerns have been raised for Lake Powell in Arizona and Utah.[97] California's reservoirs, lakes and rivers are also drying,[98], for example Lake Tahoe.[99]

Other examples of drying lakes and rivers recently highlighted in the media include: (i) The Parana River in Brazil, Paraguay and Argentina;[100]; (ii) Lake Maracaibo, one of South America's largest lakes;[101]; (iii) Lake Tuz and other lakes in Turkey.[102]; (iv) Sun Moon Lake in Taiwan.[103]; and (v) The Tigris and Euphrates rivers in Iraq.[104]

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[90] The L.A. Times writes: "The Dead Sea is dying. Drinking water is scarce. Jordan faces a climate crisis [...] the Dead Sea's level has fallen almost 100 feet." See www.latimes.com/world-nation/story/2021-04-15/the-dead-sea-is-dying-drinking-water-is-scarce-jordan-faces-a-climate-crisis.

[91] See https://www.theguardian.com/environment/2012/jan/31/china-freshwater-lake-dries-up.

[92] nytimes.com/interactive/2016/07/07/world/americas/bolivia-climate-change-lake-poopo.html.

[93] See https://reliefweb.int/report/iran-islamic-republic/iran-hamun-lake-crisis.

[94] See https://en.wikipedia.org/wiki/List_of_drying_lakes for a detailed list.

[95] See https://en.wikipedia.org/wiki/List_of_drying_lakes for a detailed list.

[96] The Washington Post writes: "The reservoir supplying electricity to 350,000 homes as well as irrigation and drinking water to about 25 million people stands at a record low." See www.washingtonpost.com/climate-environment/2022/06/27/lake-mead-reservoir-drought/.

[97] The Guardian writes: "As drought shrivels Lake Powell, millions face power crisis." See www.theguardian.com/us-news/2022/jul/13/lake-powell-drought-electricity.

[98] The Guardian writes: "California's largest reservoirs at critically low levels – signaling a dry summer ahead." See www.theguardian.com/us-news/2022/jun/24/california-drought-reservoirs-water-levels.

[99] See www.theguardian.com/us-news/2021/oct/13/lake-tahoe-water-level-drought-climate-change.

[100] The Guardian writes: "Paraguay on the brink as historic drought depletes river, its life-giving artery." See www.theguardian.com/global-development/2021/sep/27/paraguay-severe-drought-depletes-river.

[101] The Guardian writes: "Oil slicks and algae blooms marring Venezuela's largest lake are visible from space." See www.washingtonpost.com/world/2021/10/07/oil-pollution-lake-maracaibo-venezuela/.

[102] AP News writes: "Experts say Lake Tuz is a victim of climate change-induced drought." See apnews.com/article/climate-science-business-droughts-environment-137e6f52a8fe14db981a45d19e8907d1.

[103] The Guardian writes: "Parched Taiwan prays for rain as Sun Moon Lake is hit by drought. Taiwan's Sun Moon Lake is so low that parts of it have dried and turned to grass." See https://www.theguardian.com/environment/2021/may/09/parched-taiwan-prays-for-rain-as-sun-moon-lake-is-hit-by-drought.

[104] The Washington Post writes that "Where civilization emerged between the Tigris and Euphrates, climate change is poisoning the land and emptying the villages. [...] Years of below-average rainfall have left Iraqi farmers more dependent than ever on the dwindling waters of the Tigris and Euphrates." See

B Data Appendix for the Main Reduced-Form Analysis

Total surface water area. Total surface water area (sq km) over time was obtained from combining the following main sources: Olivry et al. (1996), Sédick (n.d.), FAO (2009), Comission du Bassin du Lac Tchad (2015), Okpara et al. (2016), and Ighobor (2019).

Chari-Logone River System. The GIS shapefile of the "main rivers" (major rivers) of the Chari-Logone system was obtained from the Landscape Portal. The shapefile for the "other streams" (minor rivers) of the system was obtained from FAO/GeoNetwork.

Water Discharge Rates. The historical water flow data for various sites of the Chari-Logone river system was obtained from DE/FIH/GRDC & UNESCO/IHP.[105]

Temperature & Rainfall. To obtain annual rainfall and average monthly temperature in each subdistrict-year, we use the *Terrestrial Air Temperature and Precipitation: Monthly & Annual Time Series (1900-2017)* V5.01 of Willmott and Matsuura (2001, 2021). The data is reported at a 0.5 by 0.5 degree grid resolution ($\approx$ 55 x 55 km).[106]

C Details on the Chari-Logone River System

Rainfall in the Central African Republic (CAR). While the whole region has been impacted by climate change and declining rainfall, it is the decline of rainfall in the Northern mountainous areas of the CAR that is primarily responsible for the decline in the discharge rate of the Chari and Logone rivers and the lake's water level loss.

As seen in the left panel of Appx. Fig. E.1, mean annual rainfall (mm) was before 1962 stable in the Northern areas of CAR that correspond to the Chari-Logone river system. We then observe a significant decline starting in 1963, almost 200 mm on average between the 1950-1962 period and the 1963-1989 period. However, the decline between the early 1960s and the late 1980s is starker, at about 500 mm.[107]

The right panel shows for the four sample countries considered altogether the patterns for the subdistricts closest to the lake (the ones below the country-specific median Euclidean distance to the lake). A much smaller decline is observed for these areas. As explained later, the post-1963 decline in rainfall was caused by the lake's shrinkage itself. One can see that the decline in rainfall of these areas started in 1970, at least seven years after the one in the CAR/the beginning of the lake's shrinkage (1963).

Discharge Rates. We focus our analysis on 8 selected sites of the Chari-Logone River system for which we have historical data on the mean flow rate (m^3/s) from the 1940s to the 1980s. The data is only available until 1980 for most of them. Appx. Section B lists the source and Appx. Figure E.3 maps them. Using this data, we retrace where water has disappeared. Since Lake Chad is an endorheic lake, if it is not replenished by the Chari-Logone River system's water, most of the water evaporates and the lake shrinks.

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https://www.washingtonpost.com/world/interactive/2021/iraq-climate-change-tigris-euphrates/?itid=pr_hybrid_experimentrandom_with_top_mostshared_4_na-ans_4.

[105] Source: Global Runoff Data Center/Federal Institute of Hydrology/Germany, International Hydrological Programme/United Nations Educational/Scientific and Cultural Organization, and Unaffiliated Individual/Byron Bodo. 1985. Monthly Flow Rates of World Rivers (except former Soviet Union). Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. https://doi.org/10.5065/D6571974. Accessed 11-15-2021.

[106] Source: http://climate.geog.udel.edu/~climate/html_pages/download.html.

[107] Our climate data is reported at a 0.5 by 0.5 degree grid resolution (ppx. Section B provides the source). For this analysis, we thus select the 0.5*0.5 degree pixels containing a major river or minor river of the Chari-Logone system. We then take the average of mean annual rainfall across the selected pixels.

Subfigure (a) of Appx. Figure E.3 shows the mean discharge rate at the closest place to the lake, N'Djamena (see Appx. Fig. E.3). This is where the Chari and the Logone combine. As seen, the flow rate started decreasing c. 1963, consistent with the decline in rainfall also observed c. 1963 in the mountainous areas of the Central African Republic (CAR). The discharge rate has since then continuously declined. If we compare the mean discharge rates in 1940-1962 and after 1963 (1963-1990), we observe an annual loss of 435 m^3/s on average. The question is where the 435 m^3/s per year come from the entire river system, and whether we can confidently link this decline to the CAR. We investigate this now by studying discharge rates for seven other sites upstream.

Most of the collapse in N'Djamena came from Bousso rather than Bongor, hence the Chari rather than the Logone (Appx. Fig. E.3). As seen in Subfig. (b), the discharge rate changed little in Bongor (Logone) between before and after 1963 (annual loss of 93 m^3/s) while it dropped after 1963 in Bousso (Chari; annual loss of 342 m^3/s).[108] Water from the Chari comes from the CAR and the East of Chad. In contrast, the Logone's water comes the CAR via Doba and Cameroon via Mondou (Appx. Fig. E.3). For these two other sites, we also do not observe any significant change between vs. after 1963 (Subfig. (c)). Now, was the Chari's decline explained by river flow decline in the CAR or Chad?

We examine discharge rates in Moissala and Sarh, the entry points of CAR's rainfall into the Chari, and Am Timam, where water only comes from Chad (Appx. Fig. E.3). For Moissala and Sarh, we find annual losses between vs. after 1964 of 229 m^3/s and 107 m^3/s, respectively (Subfig. (d)). In contrast, the loss in Am Timam was 6 m^3/s only.[109] Thus, the collapse in Ndjamena came from the CAR, not Cameroon nor Chad. Also, the decline started c. 1963, consistent with the rainfall decline observed in the CAR c. 1963.

D Data Appendix - City Populations

Niger. In Niger, 166 localities reached 5,000 at least once in 1945-2012. Specifically, we have available city population estimates for the following years: 1945, 1948, 1951, 1955-1962, 1965-1968, 1977, 1988, 2001, and 2012. For the pre-1968 period, we rely on colonial and post-colonial administrative reports of city population sizes. Post-1968, we rely on population censuses (1977, 1988, 2001, 2012). However, information is patchy. When Niger was still a colony as well as just after independence, administrators would sequentially visit various regions at a time to proceed with administrative counts. As such, for 16 localities with more than 5,000 inhabitants before 1968, population is available for different years for different cities. To create a consistent series, we use exponential interpolations. There are then a few cities for which we know their population before the 1940s and in the late 1950s but not in-between. To better estimate their population c. 1950, we also consider their pre-1950 population.

For later years, there are a few cities for which the first population estimate available exceeds 5,000 by several thousands. These cities might have exceeded 5,000 in the previous years of data but we cannot be sure. To allow for this possibility, and for each city without any early estimate, we assume that their 1945 population was 1 inhabitant

[108] We actually find average losses of 86 m^3/s and 315 m^3/s. Since the data is available for different years for N'Djamena and the other sites, we use these values to obtain the percentage contributions of each upstream site, in this case 21% and 79%. We then respectively multiply -435 by 0.21 and 0.79.

[109] We actually find average losses of 258, 120 and 7 m^3/s. Since the data is available for different years for Bousso and the other sites, we use these values to obtain the percentage contributions of each upstream site, in this case 67%, 31% and 2%. We then respectively multiply -342 by 0.67, 0.31 and 0.02.

and use exponential interpolation to fill the missing years. This increases the likelihood that a city exceeds 5,000 if its value is well above 5,000 the following year of data.

Finally, total population is available in the years 1951, 1956, 1957 1958, 1959, 1960, 1961, 1962, 1969, 1988, 2001, 2012, 2013, 2014, 2015, 2016 and 2017. We can reconstruct total urban population for many of these. Note that we use city population estimates in 1968 for the year 1969 and ignore 2013-2017 since we do not have city estimates after 2012. In the end, we obtain rural population in 1951, 1956, 1957 1958, 1959, 1960, 1961, 1962, 1969, 1988, 2001 and 2012 (N = 119 subdistricts x 12 years = 1,428 obs.).

Cameroon. 186 localities reached 5,000 at any point in 1945-2005. The available years are 1945, 1950, 1953, 1956, 1958-1968, 1970, 1976, 1987 and 2005. For the pre-1976 years, we use colonial and post-colonial administrative counts. For the years 1976, 1987 and 2005, we use population censuses. Total population is available in the years 1963, 1967, 1976, 1987 and 2005. As such, we are able to reconstruct subdistrict rural population for the same years as total population (N = 113 subdistricts x 5 year = 565 obs.).

Chad. 100 localities reached 5,000 at any point in the period 1945-2009. The available years are 1945-1951, 1954-1956, 1961, 1964, 1968, 1975, 1993, 2000, and 2009. For the pre-1968 years, we use colonial and post-colonial administrative counts. For the years 1993 and 2009, we use population censuses. For the years 1975 and 2000, we use administrative population count estimates provided by Chad's *Institute of Statistics*. Total population is available in the years 1948, 1953, 1965, 1993 and 2009. Since we used 1964-1968 total population data for the year "1965", we can reconstruct rural population for the same years as total population (N = 138 subdistricts x 5 year = 690 obs.).

E Data Appendix - Model Inputs

Land suitability. We rely on 2000 information from the FGGD Digital Atlas of FAO (2007). Their *crop suitability index* (CSI) measures the "suitability of currently available land for rainfed crops, using maximising crop and technology mix." Their *pastoral suitability index* (PSI) measures the suitability of currently available land for pasture. The data is reported at a 0.08 by 0.08 degree grid resolution ($\approx$ 9 x 9 km).[110]

Expenditure Shares. For the year 2010, we rely on the World Bank's *Global Consumption Database*. They estimate the shares based several household or budget surveys.[111]

For the year 1963, we cannot rely on national household or budget surveys as such surveys did not exist then. However, there were city-specific surveys as well as region-specific surveys that focused on the regions' rural areas.[112] We first use the city-specific

[110] They consider 171 crops. Url for the data: https://data.apps.fao.org/map/catalog/srv/eng/catalog.search#/metadata/6a7863d0-892d-11db-b9b2-000d939bc5d8, last accessed 09-01-2021.

[111] Url: https://datatopics.worldbank.org/consumption/, last accessed 07-11-2022. The four surveys used by the World Bank are: (i) Cameroon: *Enquete Camerounaise aupres des Menages III* 2007; (ii) Chad: *Enquete sur la Consommation et le Secteur Informel au Tchad 2003*; (iii) Niger: *Enquete Nationale sur le Budget et la Consommation des Menages* 2007; and (iv) Nigeria: *Living Standards Survey* 2009.

[112] (A) Cameroon: (i) Winter, G. (1967). *Methodologie des enquetes "niveau de vie" en milieu rural Africain. Bilan des 3 enquetes effectuees de 1961 a 1965 au Cameroun.* Yaounde: ORSTOM; (ii) Gouvernment du Cameroun (1965). *Etudes Socio-Economiques sur le Nord-Cameroun.* Ministere de l'Economie Nationale, Direction de la Statistique; (iii) Gouvernment du Cameroun (1967). *Enquete sur le niveau de vie a Yaounde - Cameroun 1964-1965.* Direction de la Statistique de la Republique Federale du Cameroun; and (iv) Gouvernment du Cameroun (1967). *Le Niveau de vie des populations de l'Adamaoua.* Direction de la Statistique de la Republique Federale du Cameroun. (B) Chad: Ministere du plan et de la cooperation

survey reports to obtain the expenditure shares for the *urban areas* of each country.[113] We then use the region-specific survey reports to obtain the expenditure shares for the *rural areas* of each country.[114] Lastly, we use the urban share of each country circa 1965 (source: UN (2018)) to obtain the expenditure shares for the whole country.[115]

Note that we use the housing expenditure shares in urban areas as a proxy for the same shares nationally. Indeed, information in rural areas is limited. When information is available, it is unclear if imputed rents are included. We thus believe that the rural housing expenditure shares reported in the surveys are significantly under-estimated.

Finally, we obtain regional expenditure shares using the population of each country c. 963 and 2010 (source: UN (2019)). See Appx. Table E.8 for the shares in each year.

Kuri cattle breed data. For each country and circa the year 1965 as much as possible, we obtain the total number of cattle heads in more or less the same areas that had Kuri cattle historically. To do so, we use the following sources for each country: (i) Cameroon (early 1970s): Pamo and Pieper (1987); (ii) Chad (1966): IBRD (1968); (iii) Niger (1964): Republique du Niger (1964); and (iv) Nigeria (1968): Miller et al. (1968).

GDP Shares. We rely on several sources to obtain the GDP shares of each sector in Cameroon (1963-64-68), Chad (1963), Niger (1962-68), and Nigeria (1965-66).[116]

F Model Validation

F1. Validation of the Livestock Production Distribution

For all countries, we compare: (i) the model-predicted distribution of livestock GDP c. 1963; (ii) the actual distribution of livestock units c. 1963 which we obtain from

du Tchad (1969). *Enquete socio-économique au Tchad, 1965.* Paris: Republique francaise, Secretariat d'Etat aux affaires etrangeres: INSEE, Departement de la coopéeration; (C) Niger: (i) Bernus, Suzanne (1964). *Niamey: population et habitat.* Etudes nigeriennes: Doc, IFAN. Republique du Niger; and (ii) Gouvernment du Niger (1962). *Etude démographique du Niger (Enquete par sondage, 1960). 1er fascicule : données collectives. Résultats définitifs.* Republique du Niger, Mission economique et pastorale; (D) Nigeria: U.S. Dept of Commerce (1964). *Market for U.S. products in Nigeria.* Bureau of Intl Commerce.

[113] For Cameroon and Nigeria, we rely on 3 and 5 cities, respectively. To obtain an urban average, we use as weights the population of each city circa 1965. For Chad and Niger, since we have only 2 cities in Chad and 1 city in Niger, and given how similar Chad's and Niger's economies and geographies are and were, we combine these 3 cities to obtain an urban average for Chad and Niger combined.

[114] For Cameroon, we have 3 rural regions. To obtain a rural average, we use as weights the population of each region c. 1965. Regional data is unavailable for Nigeria. Since Cameroon is the closest country in terms of economic development as well as physical and economic geography, we use rural Cameroon as a proxy for rural Nigeria. For Chad and Niger, since we have only 1 Southern region in Chad and 2 Northern regions in Niger, and given how similar Chad's and Niger's economies and geographies are and were, we combine these 3 regions to obtain a rural average for Chad and Niger combined.

[115] Since Chad and Niger had slightly different urban shares in 1963, their overall expenditure shares vary even if their "urban" and "rural" expenditure shares do not (since we combine Chad and Niger).

[116] The sources are: (A) Cameroon: (i) IBRD. 1966. *L'economie de la Republique Federale du Cameroun.* Washington, DC: Banque Internationale pour la Reconstruction et le Developpement; (ii) Carter, M. and McLeroy, G. 1968. *Range Management and Livestock Industry: Chad Basin.* Prepared for the Chad Basin commission. (B) Chad: (i) IBRD. 1968. *L'economie de la Republique Federale du Tchad.* Washington, DC: Banque Internationale pour la Reconstruction et le Developpement; (C) (i) Government of Niger. 1962. *Annuaire Statistique.* Niamey: Commissariat General au Plan; (ii) Carter, M. and McLeroy, G. 1968. *Range Management and Livestock Industry: Chad Basin.* Prepared for the Chad Basin commission; and (D) Nigeria: (i) Government of Nigeria. 1968. *Annual Abstract of Statistics.* Lagos: Federal Office of Statistics.

administrative sources.[117]; (iii) the distribution of cattle heads c. 1963 as provided by Lunde and Lindtjørn (2013) (henceforth, LL13). LL13 rely on historical cattle census data compiled by Deshler (1963). Cattle GDP typically accounts for 90% of livestock GDP; and (iv) a index of transhumant pastoralism inspired by McGuirk and Nunn (2022) (using their broad definition) based on the *Ethnographic Atlas* of Murdock (1967).

One important issue is that administrative and census-based measures of livestock units/cattle heads are often based on livestock/cattle markets, i.e., where the units/heads are sold rather than where they are "produced." When the measures are based on production, another issue is that the data overwhelmingly represent the dry season, when the spatial concentration of herders facilitates counting by government agencies. Indeed, transhumant pastoralists leave their homeland areas in the north when the wet season ends and pastures are too dry. As a result, the distributions are biased towards southern areas. These issues particularly affect Chad and Niger, two Sahelian countries where livestock production is highly concentrated in the north and herders move south to find greener pastures during the dry season and access markets.

Furthermore, this Southern bias increases if the data sources used over-represent cattle, which has to be bred in colder (more southern) latitudes. In contrast, our model-based livestock GDP measures include all types of animals, including goats, sheep and camels which can be bred in warmer (more northern) latitudes.

Cameroon. Appx. Fig. E.8 shows the c. 1963 maps for Cameroon. Panel (b) shows the number of total livestock units per sq km based on administrative data (available for 9 regions only).[118] Panel (a) shows the model-based estimates for the same 9 regions. The two measures are visually correlated. Panel (d) shows the number of cattle heads per sq km (N = 113 subdistricts). It is correlated with our model-based measure of livestock GDP per sq km. Finally, the information that we obtain from the historical location of transhumant pastoralist groups (panel (e)) is limited, as only one ethnic group in the north classifies as such according to the definition of McGuirk and Nunn (2022). However, the production data confirms that more ethnic groups indeed raised livestock.

Chad. See Appx. Fig. E.9. Panel (b) shows the number of total livestock units per sq km based on administrative data (N = 10 regions only).[119] Panel (a) shows the model estimates for the 10 regions. The two measures are visually correlated except for the fact the model shows more production in the north. Indeed, the administrative data overly represents the dry season when livestock is moving south towards markets. Panel (d) shows the number of cattle heads per sq km (N = 138 subdistricts). It is correlated with our model measure of livestock GDP per sq km except for the fact that LL13 overly represents the dry season when livestock is moving south towards markets (e.g., LL13 does not report any information for the northern-most subdistricts). Since LL13 is based on livestock markets, it also under-estimates production in the southern-most subdistricts where herders directly sell their livestock in neighboring Cameroon or Nigeria. Also, LL13 focuses on cattle and ignores goats, sheeps and camels, which are bred at higher latitudes.[120] Finally, the validity of our model predictions can be verified

[117]Administrative sources usually provide data on the total number of livestock heads for each animal group (e.g, cattle, chicken, and camels). To obtain a single measure, we convert each animal type into total livestock units (TLUs) using FAO conversion values for Sub-Saharan Africa (FAO, 2003).

[118]Sources: Johnson (1969) and Vaast et al. (1996).

[119]Sources: Secrétariat d'État aux relations avec les États de la Communauté (1960).

[120]In the B.E.T. (Chad's northern-most region), cattle represents 6% of total livestock units vs. 46% of at

by looking at the historical distribution of transhumant pastoralist groups (panel (e)).

Niger. See Appx. Fig. E.10. Panel (b) shows the number of total livestock units per sq km based on administrative data (N = 16 regions).[121] Panel (a) shows the model estimates for the 16 regions. The two measures are visually correlated except for the fact the model shows more production in the north. Indeed, administrative data overly represents the dry season when livestock is moving south towards markets. In the East, livestock is sold directly in Nigeria and Cameroon. The administrative data thus underestimates production there. Panel (d) shows the number of cattle heads per sq km (N = 119 subdistricts). It is correlated with our model measure of livestock GDP per sq km except for the fact that LL13 overly represents the dry season when livestock is moving south towards markets (e.g., LL13 does not report any information for the northern-most subdistricts). Also, LL13 focuses on cattle and ignores goats, sheeps and camels, which are bred at higher latitudes. In contrast, panel (e) shows that transhumant pastoralist groups reside in regions which our model predicts to have livestock.

Nigeria. See Appx. Fig. E.11. Panel (b) shows the number of total livestock units per sq km based on administrative data (N = 10 regions).[122] Panel (a) shows the model estimates for the 10 regions. The two measures are visually correlated, with less livestock production in the center. Panel (d) shows the number of cattle heads per sq km (N = 83 subdistricts). It is visually strongly correlated with our model-based measure of livestock GDP per sq km. Indeed, Nigeria does not have the same mismeasurement issues as Chad and Niger. Finally, little can be learned from panel (e), as few ethnic groups are classified as transhumant pastoralist in Murdock (1967). Even then, the few transhumant pastoralist groups appearing as such in Murdock (1967) are located in areas where we see a lot of livestock in the other sources including our model.

F2. Validation of the exogenous amenity distribution

Appx. Table E.13 shows that fundamental amenities ($\bar{u}_i$) are strongly correlated with the location of educational and health facilities c. 1963. The table and table notes show which controls are used in which column and how the indexes are constructed.

Cameroon. For 85 *arrondissements* in Cameroon c. 1963, we know the respective number of "lycees" (high schools), "colleges" (secondary schools) and "cours complementaires / ecoles normales" (primary schools). To construct an education index, we use the fact that there are 6 high schools, 24 secondary schools and 71 primary schools in the whole country. That makes high schools and secondary schools 11.8 and 3.0 more "valuable" than primary schools, respectively. Next, Log((education index/area) = log((11.8*high schools + 3.0*secondary schools + 1*primary schools)/area). We additionally use Log(education index/total population c. 1963). We then proceed similarly to construct a health index, obtaining Log(health index/area) = log((11*public hospitals + 15.7*private hospitals + 7.9*departmental centers of preventive medicine + 3*private dispensaries + 1*public dispensaries)/area). We additionally use Log(health index/total population c. 1963).[123]

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the country level (Secrétariat d'État aux relations avec les États de la Communauté, 1960).

[121] Sources: Commissariat Général au Plan (1965).

[122] Sources: Fréchou (1966) and Federal Office of Statistics (1969).

[123] Main source for the three education variables c. 1963: *Premier Plan Quinquenal et Development Economique et Social* (1961). Minitere des Finances et du Plan. Source for the five health variables c. 1963: *Atlas du Cameroun, Planche IX* (1967). Institut de Recherches Scientifiques du Cameroun.

When instead considering as predictors the three underlying education components and the five underlying health components, we simultaneously use the log of (their value / area) and the log of (their value / population c. 1963). Lastly, since we have initial exogenous amenity values for 113 subdistricts, we obtain the mean amenity value of each arrondissement using the subdistricts' populations c. 1963 as weights.

As seen in Appx. Table E.13, the adjusted R2 is 0.82 if we simultaneously include the log of the education and health indexes/area and the log the indexes/population and 0.84 if we also include the square of these logs. If we simultaneously include the log of the individual components/area and the log of the individual components/population, the adjusted R2 is 0.77. Adding their squares, the adjusted R2 increases to 0.82. Thus, the adjusted R2 is ≈ 0.8 for Cameroon. We proceed likewise for other countries.

Chad. Data is available for 14 *prefectures* c. 1963 only (these are first-level administrative units). We use data on the location of: (i) education: high schools, secondary schools, primary schools; and (ii) health: hospitals, medical centers, epidemics control centers, infirmaries, and dispensaries.[124] With the indexes (first two columns), we obtain adjusted R2 $\approx$ 0.6-0.7. Lastly, given the limited number of observations, we cannot simultaneously include the education and health components. Instead, we try only adding the education component measures or the health component measures. The adjusted R2 is $\approx$ 0.55-0.6. Of course, with the small number of observations, the first specification with the index measures is more reliable (adjusted R2 ≈ 0.7).

Niger. Data is available 24 *subdivisions* c. 1963. We use data on the location of high schools, secondary schools and primary schools for the education index, and hospitals, health centers, small hospitals, nurseries and dispensaries for the health index.[125] With the index measures only, we get adjusted R2 ≈ 0.75. Using the component measures instead, we get adjusted R2 $\approx$ 0.8-0.9. Therefore, for Niger, the adjusted R2 is ≈ 0.8.

Nigeria. Health data is available for 29 *provinces* whereas education data is available for 10 *states*. We use data on universities, secondary schools (incl. high schools) and primary schools to create the education index, and data on federal general hospitals, federal special hospitals, federal infectious diseases hospitals, federal maternity centres, federal dispensaries, regional/local general hospitals and nursing homes, regional/local special hospitals, regional/local infectious diseases hospitals, regional/local maternity centres and rural health centres, and regional/local dispensaries to create the health index.[126] We show the health results first, focusing on the health index measures given the high number of underlying health components. The adjusted R2 is ≈ 0.75. For the education measures, we get lower adjusted R2 ≈ 0.45 but we have 10 observations only.

F3. Model Extensions

F3.1. Nested CES Preferences

We consider variable expenditure shares since expenditure shares may respond endogenously to CC shocks. We then modify the utility function (9) as follows:

[124] Source for education: *Statistiques Scolaires 1967-1968* (1968). Ministere de L'Education Nationale. Health: *Atlas Practique du Tchad 1967* (1972). Institut National Tchadien pour les Sciences Humaines.

[125] Source for education: *Annuaire Statistique 1962* (1962). Commisariat General au Plan. Health: *Carte administrative, infrastructure sanitaire, 1964* (1968). Republique du Niger.

[126] Source for education: *Statistics of Education in Nigeria, 1968* (1969). Federal Ministry of Education Health. Health: *Annual Abstract of Statistics 1963* (1964). Federal Office of Statistics.

$$U_i = \epsilon_{ij} \left(\frac{T_i}{\delta}\right)^{\delta} \left(\sum_s \tilde{\alpha}_s \left(\frac{C_{is}}{1-\delta}\right)^{\frac{\xi-1}{\xi}} \right)^{\frac{(1-\delta)\xi}{\xi-1}}, \tag{9}$$

where the expenditure share of land is still constant and equal to δ. The parameters $\tilde{\alpha}_s$ are taste shifters specific to sector s. As a result, the expenditure shares α_s of agriculture, livestock, fishing, and the urban sector are no longer constant. In particular, by the properties of CES utility functions, the expenditure share in sector s from location i is:

$$\alpha_{is} = \frac{\tilde{\alpha}_s^{\xi-1} P_{is}^{1-\xi}}{\sum_k \tilde{\alpha}_k^{\xi-1} P_{ik}^{1-\xi}},$$

where P_{is} is the aggregate price index faced by location i in sector s and takes the same form as in the main text:

$$P_{is}^{1-\sigma_s} = \sum_j p_{jis}^{1-\sigma_s},$$

$$Q_i = \left(\sum_k \tilde{\alpha}_k^{\xi-1} P_{ik}^{xi-1} \right)^{\frac{1}{1-\xi}}, \qquad P_i = r_i^{\delta} Q_i^{1-\delta}$$

where p_{jis} is the price charged by producers from location j in sector s to consumers in location i. Then, the indirect utility function of consumers in location i without the idiosyncratic shock is:

$$V_i = \frac{u_i(w_i + r_i t_i + q_i \tilde{w}_i)}{P_i}.$$

Quantification-wise, we proceed as in the main text. However, in the model inversion, we include an additional step in which we invert the model to identify the taste shifters $\tilde{\alpha}_s$ to match the expenditure shares observed c. 1963. We use a value of $\xi = 2$ that we take from Edmond et al. (2015) that studies how variable markups affect the gains from trade using the Atkeson and Burstein (2008) model in which this elasticity is fundamental. Then, we proceed to run the same counterfactuals as in the main text.

F3.2. Non-Homothetic Preferences

Expenditure shares are no longer constant in this case. However, the main difference with the previous case is that the expenditure shares for each good depend on income. We follow the model from Comin et al. (2021) in which the extent to which expenditure shares respond to income changes depends on a parameter that can vary across sectors. The utility function of consumers in location i is given by:

$$U_i = \left(\frac{T_i}{\delta}\right)^{\delta} \left(\frac{C_i}{1-\delta}\right)^{1-\delta},$$

$$\sum_s \tilde{\alpha}_s^{\frac{1}{\xi}} C_i^{\frac{\epsilon_s}{\xi}} C_{is}^{\frac{\xi-1}{\xi}} = 1,$$

where $\tilde{\alpha}_s$ are taste-shifters, ξ is the elasticity of substitution across sectors, and ϵ_s is the non-homothetic elasticity of substitution. In the case of $\epsilon_s < 1-\xi$, the good is a necessary good, and the expenditure share decreases with income. The opposite occurs if $\epsilon_s > 1-\xi$. In that case, the good is a luxury good, and the expenditure increases with income. The price indices of the sectors without including land are:

$$Q_i = \left(\sum_s \left(\tilde{\alpha}_s P_{is}^{1-\xi} \right)^{\frac{1-\xi}{\epsilon_s}} \times \left(\phi_{is}((1-\delta)I_i)^{1-\xi} \right)^{\frac{\epsilon_k - (1-\xi)}{\epsilon_k}} \right)^{\frac{1}{1-\xi}},$$

where ϕ_{is} is the sectoral expenditure share given by:

$$\phi_{is} = \tilde{\alpha}_{is} \underbrace{\left(\frac{P_{is}}{Q_i} \right)^{1-\xi}}_{\text{Substitution}} \times \underbrace{\left(\frac{(1-\delta)I_i}{Q_i} \right)^{\epsilon_k - (1-\xi)}}_{\text{Non-homotheticity}}$$

This system of equations does not have an explicit solution for the expenditure shares. However, a unique and implicit solution exists for the expenditure shares and the aggregate price index Q_i. We use the following parameters based on the work from Conte (2021) and Nath (2022): $\xi = 0.26$ and then $\epsilon_s = 0.29$ for the three primary sectors (agriculture, fishing, and livestock) and ${}_s = 1$ for the urban good. As in the previous case, we add another moment to the model inversion in which we match the aggregate sectoral expenditure shares from 1963 to identify the taste shifters $\tilde{\alpha}_s$.

F3.3. Including the Rest of the World (RoW)

We add the RoW as an additional location. This additional ingredient may be relevant since workers could also migrate to the RoW or substitute local goods for imports, possibly smoothing the aggregate losses from the lake's shrinkage.

- In terms of land supply, we use the FGGD data of FAO (2007) and obtain that the total land area of the RoW is equal to 28.4x the total land area of the four countries.
- In terms of water supply, we calculate the sea water supply (area) of each country using a 13 km buffer from each country's coast (also assuming countries cannot fish in other countries' waters). Doing so, we obtain that the RoW has approximately 114 times the total water area of the four countries of study.
- For the productivity measures, we use the FGGD data of FAO (2007) and find that agricultural productivity in the RoW is on average 0.98 times the average productivity of the four countries. For livestock, we find 2.6 times. We normalize water productivity to 1. Finally, we find that the RoW was 2.3 more urbanized (in terms of urban share) than the four countries considered altogether.[127] We thus assume that urban productivity is 2.3 times higher in the RoW on average.
- To calculate trade costs, we assume a tariff of 20% (similar to what we used within our region) and that the cost of Euclidean distance to Europe's largest port – Rotterdam – is $\approx$ 3x times lower for ships than by road within our region (δ = 0.03 instead of 0.08 for road-based travel).[128] This suggests an iceberg cost of at least 13, which we believe is reasonable given the ratios of imports and exports to GDP were about 10% c. 1963, suggesting an iceberg cost of at least 10 (since imported goods and locally produced goods are not necessarily homogenous).
- To get migration costs, we use the Euclidean distance to Rotterdam and apply the same parameter as for distance-based migration within our region (0.05).
- We invert the model to recover initial prices and amenities (incl. for the RoW).

[127] Source: World Urbanization Prospects database of the United Nations. Last accessed 07-14-2023.

[128] Within our region, we use 80 kph, 60 kph, 40 kph and 12 kph for highways, paved roads, improved roads, and dirt roads, respectively. Cargo ships typically travel at a speed of 13-15 knots, or 24-28 kph. We thus see these results as possibly over-estimating the minimizing impact of trade with the RoW.

C. Web Appendix Figures and Tables

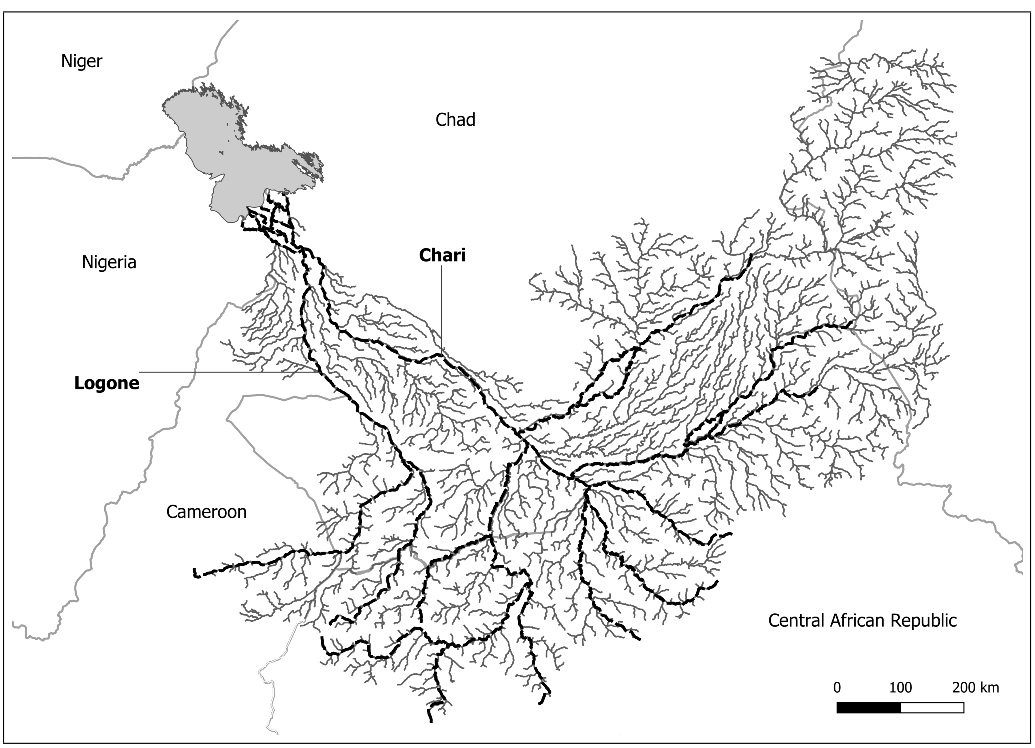
Figure E.1: Annual Rainfall in the Central African Republic vs. the Sample Countries

(a) Central African Republic: Areas of the Chari-Logone River System that Feed Lake Chad's Water

(b) Four Countries of Study: Subdistricts Below the Country-Specific Median Distance to the Lake

Notes: The figures show mean annual rainfall (mm) in each year t: (a) for the areas of the Central African Republic located within 10km of any of the major or minor river of the Chari-Logone river system; and (b) for the subdistricts of Cameroon, Chad, Niger and Nigeria that are close to Lake Chad, i.e. for the subdistricts whose Euclidean distance to the lake is below the median Euclidean distance to the lake in the sample in each country. See Web Data Appendix Section B for details on the sources.

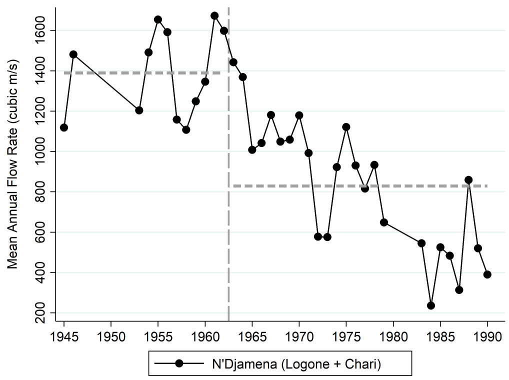
Figure E.2: Chari-Logone River System Feeding Lake Chad, Including Minor Rivers



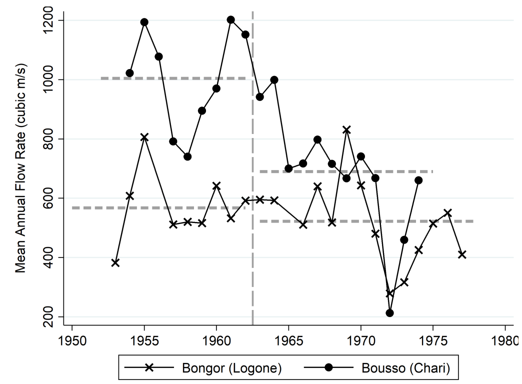
Notes: The Chari and Logone rivers provide almost all of Lake Chad's water. We show in bold the main rivers of the Chari-Logone river system. In grey, we show other streams associated with the extended Chari-Logone river system. See Web Data Appendix Section B for details on the sources.

Figure E.3: Mean Annual Flow Rate (mm) at Various Sites, 1940s-1980s

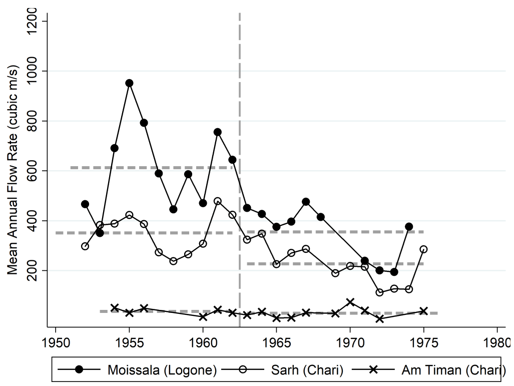
(a) N'Djamena (Chari + Logone)



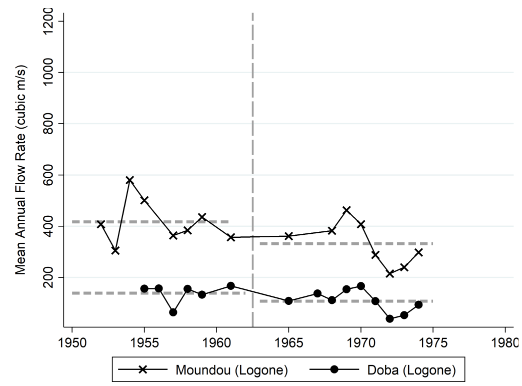
(b) Bongor (Logone) vs. Bousso (Chari)



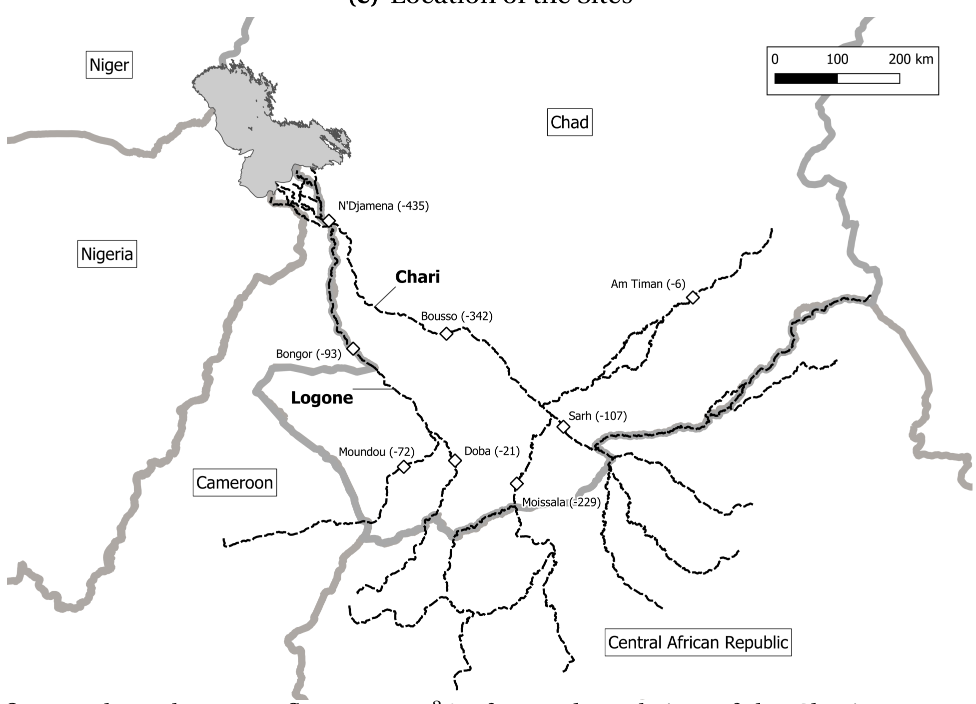
(c) Upstream Sites of Bousso (Chari)



(d) Upstream Sites of Bongor (Logone)

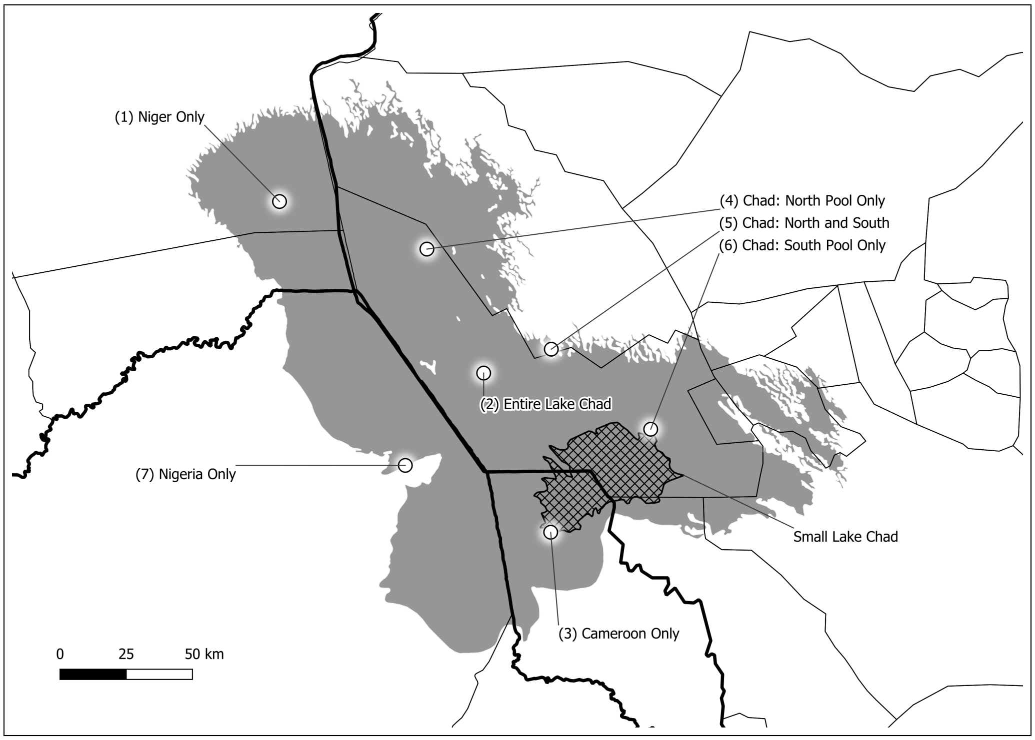


(e) Location of the Sites



Notes: The figures show the mean flow rate (m^3/s) for 8 selected sites of the Chari-Logone river system and for each year with available data and focusing on the 1940s-1980s. We also report the average of the mean rates for each site and each period 1940-1962 and 1963-1990 (for figures (b), (c) and (d), we focus on 1963-1980 due to lack of data in the 1980s). Figure (e) shows the main rivers of the system and the location of the sites. See Web Appx. Sections B and C for details on the sources and analysis, respectively.

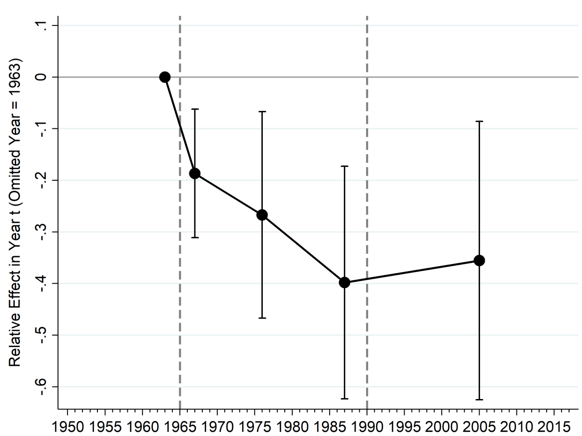
Figure E.4: Location of the Selected Country-Specific Centroids of Lake Chad



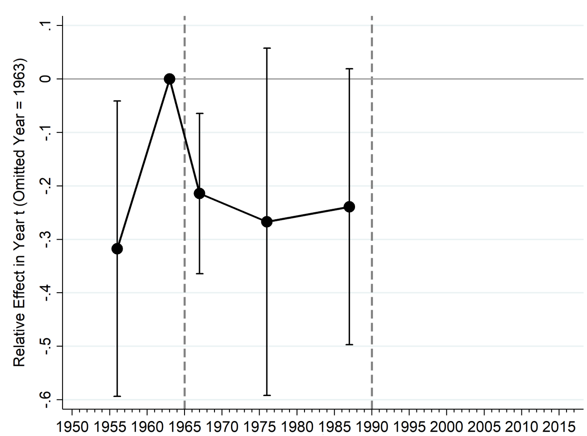
Notes: This figure shows the full (pre-1963) and small (c. 1990 and c. 2020) Lake Chad as well as the centroids of Lake Chad that we consider for each of the four countries of study.

Figure E.5: Relative Population Effect of Proximity to Lake Chad, Cameroon, Pre-Trends

(a) Cameroon Subdistricts (N=113) (1963-2005)

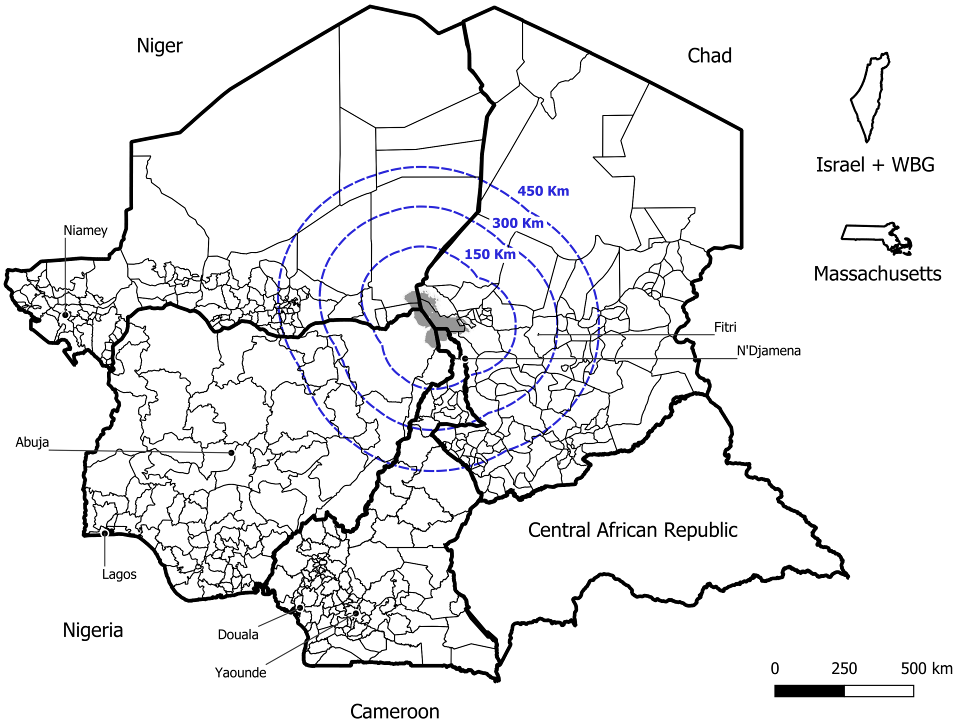


(b) Cameroon Districts (N=47) (1956-2005)



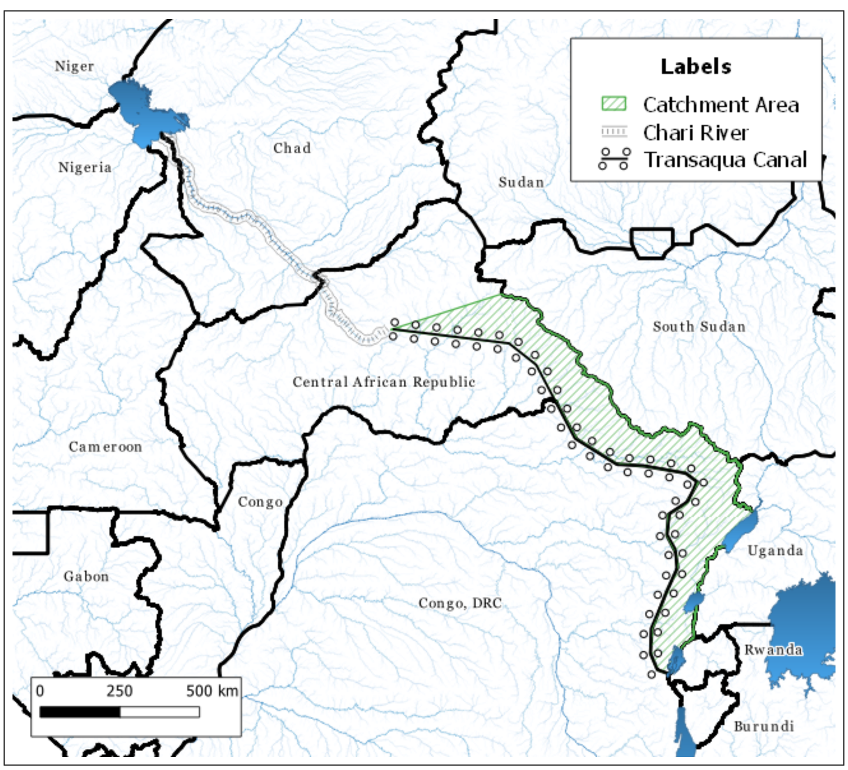
Notes: Subfigure (a) shows for Cameroonian subdistricts the relative total population effects of proximity to Lake Chad (omitted year = 1963). Subdistrict sample (1963-2005): 113 subdist. x 5 yrs = 565. We include subdistrict and year FE, district-specific linear trends, and time-invariant controls interacted with year FE: log Euclidean distances to the largest and capital cities and their square, latitude, and two dummies for whether the subdistrict contains major or minor rivers of the Logone-Chari river system. Subfigure (b) shows for Cameroonian districts the relative total population effects of proximity to Lake Chad (omitted year = 1963). District sample (1956-2005): 47 dist. x 6 yrs = 282. We include district and year FE, district-specific linear trends, and the time-invariant controls interacted with year FE. With district trends, the district-level effect for the year 2005 is not estimated. The dashed vertical lines show the years the lake started to decline (c. 1965) and recover (c. 1990). 90% c.i. (Conley SE 100 Km).

Figure E.6: Lake Chad Region and Selected Distance Bins for the Bin Specification



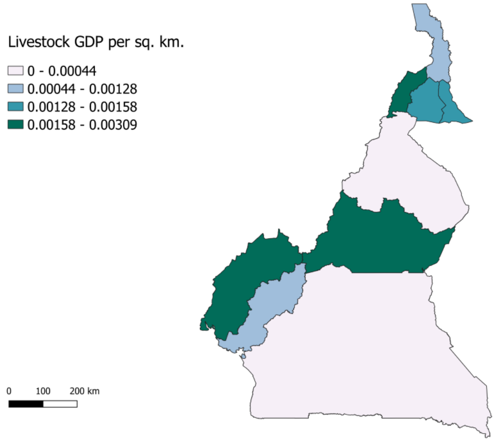
Notes: This figure shows the three distance bins used in the flexible bin specification: 0-150 km, 150-300 km, and 300-450 km (based on the Euclidean distance from the subdistrict's centroid to the selected Lake Chad centroid, in this case the centroid of the portion of Lake Chad that lies within the country's territory). We define the "Lake Chad Region" as subdistricts within 450 km from Lake Chad.

Figure E.7: Map of the Transaqua Project

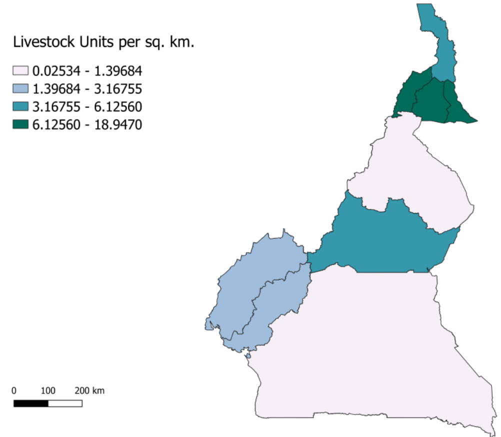


Notes: The Transaqua project proposes the construction of a 2,400-km canal aimed at diverting enough water from the Congo River Basin in the Democratic Republic of the Congo to replenish Lake Chad.

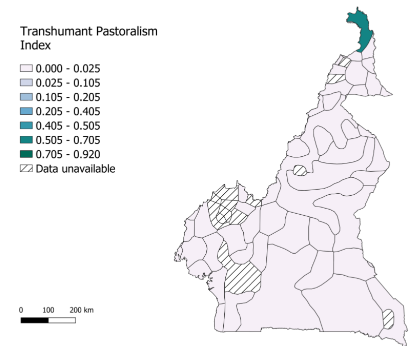
Figure E.8: Validation of the Model: Livestock Distribution in Cameroon c. 1963



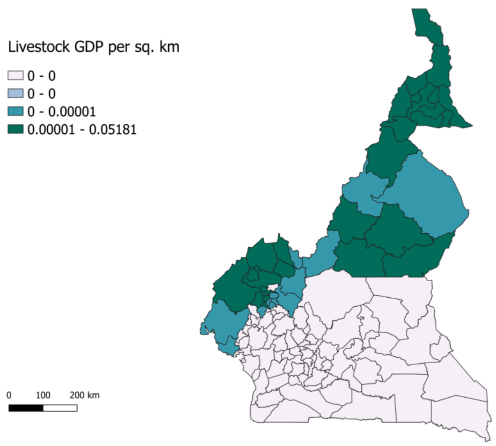
(a) Livestock per sq km (model)



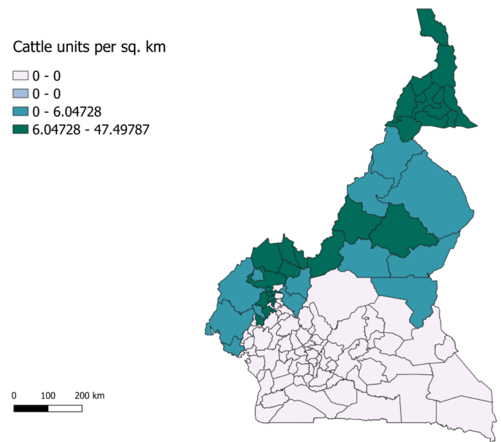
(b) Livestock per sq km (admin data)



(e) Transhumant pastoralism



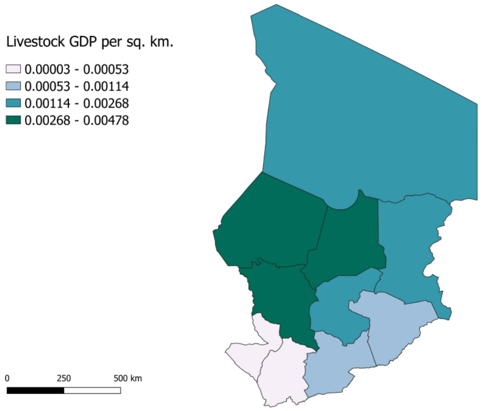
(c) Livestock per sq km (model)



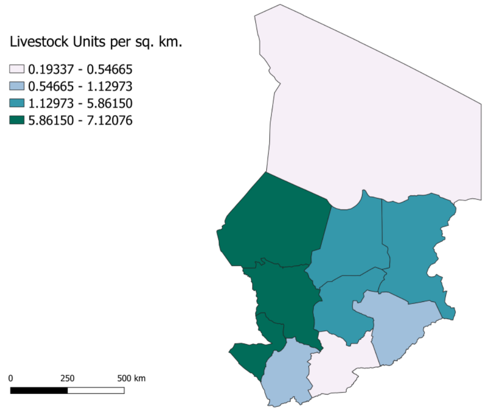
(d) Cattle per sq km (LL 2013)

Notes: These figures show for Cameroon c. 1963 how the spatial distribution of livestock predicted by the model compares to the distribution obtained from alternative sources. All measures of livestock distribution are normalized by area. Panels (a) and (b) compare the distribution of livestock obtained from the model and from Cameroonian administrative sources, respectively. The size and shape of geographical units (9 units) is determined by the level of aggregation of the data in the administrative sources. Panels (c) and (d) compare the distribution of livestock obtained from the model and the distribution of cattle according to Lunde and Lindtjørn (2013) based on 1963 data. The geographical units (113 units) match those used for the reduced form analysis. Finally, panel (e) presents an index of transhumant pastoralism created by McGuirk and Nunn (2022) based on Murdock's *Ethnographic Atlas*. We recreated the index data ourselves using the map in their study.

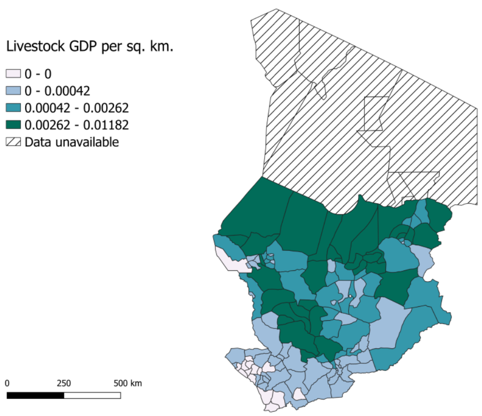
Figure E.9: Validation of the Model: Livestock Distribution in Chad c. 1963



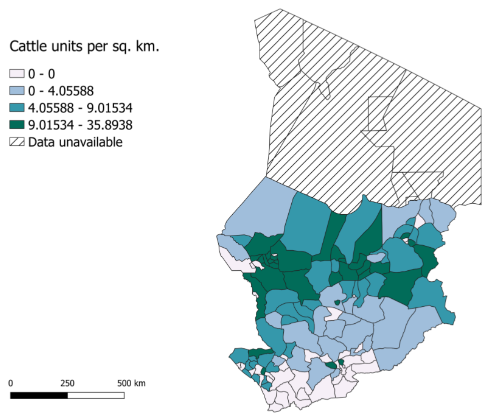
(a) Livestock per sq km (model)



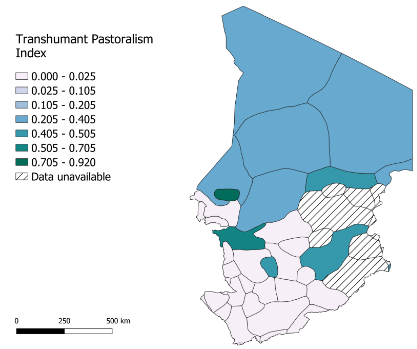
(b) Livestock per sq km (admin data)



(c) Livestock per sq km (model)



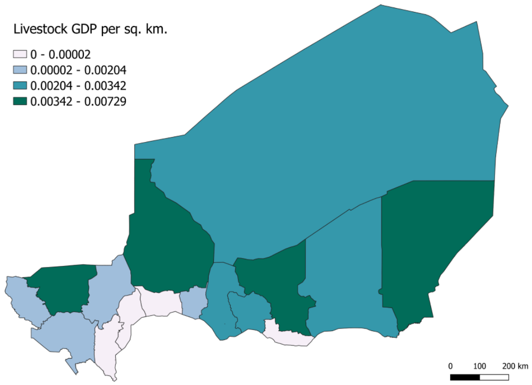
(d) Cattle per sq km (LL 2013)



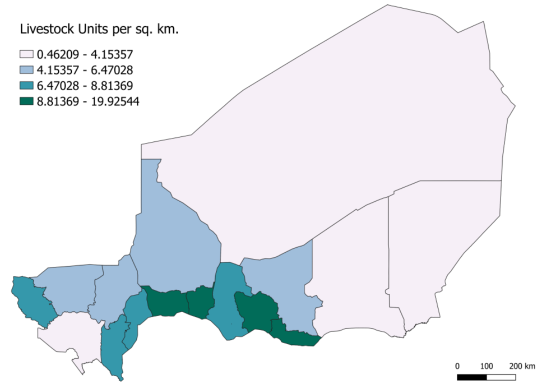
(e) Transhumant pastoralism

Notes: These figures show for Chad circa 1963 how the spatial distribution of livestock predicted by the model compares to the spatial distribution obtained from alternative sources. All measures of livestock distribution are normalized by area. Panels (a) and (b) compare the distribution of livestock obtained from the model and from Chadian administrative sources, respectively. The size and shape of geographical units (10 units) is determined by the level of aggregation of the data in the administrative sources. Panels (c) and (d) compare the distribution of livestock obtained from the model and the distribution of cattle according to Lunde and Lindtjørn (2013) based on 1963 data. The geographical units (138 units) match those used for the reduced form analysis. Finally, panel (e) presents an index of transhumant pastoralism created by McGuirk and Nunn (2022) based on Murdock's *Ethnographic Atlas*. We recreated the index data ourselves using the map in their study.

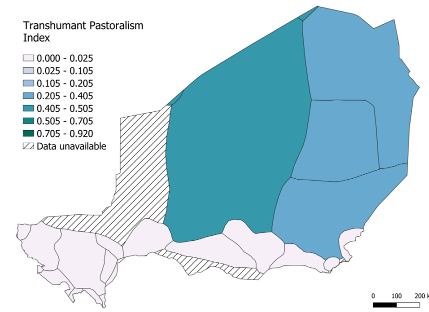
Figure E.10: Validation of the Model: Livestock Distribution in Niger c. 1963



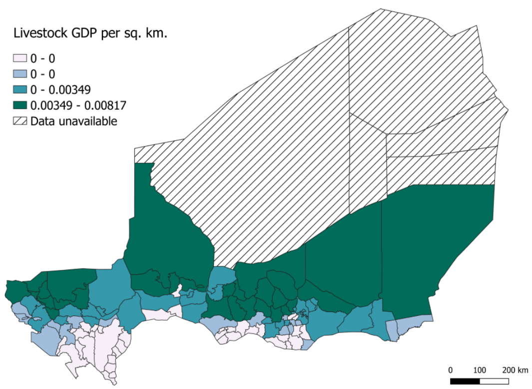
(a) Livestock per sq km (model)



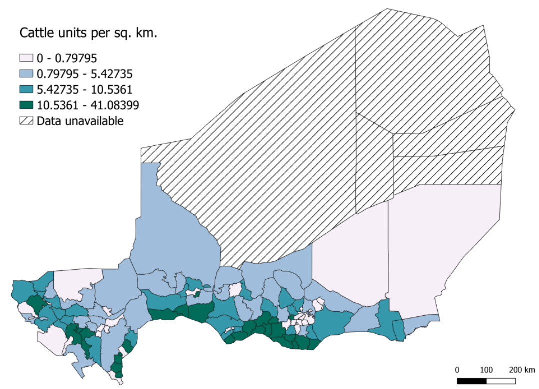
(b) Livestock per sq km (admin data)



(e) Transhumant pastoralism



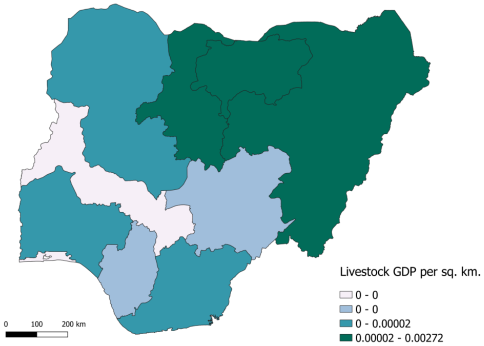
(c) Livestock per sq km (model)



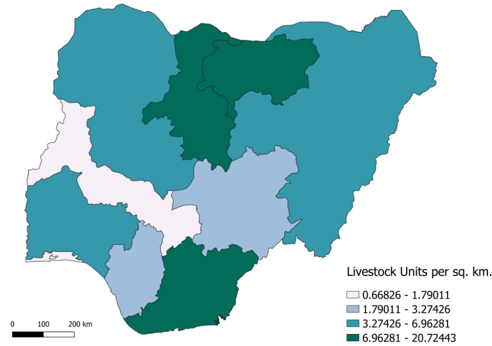
(d) Cattle per sq km (LL 2013)

Notes: These figures show for Niger circa 1963 how the spatial distribution of livestock predicted by the model compares to the spatial distribution obtained from alternative sources. All measures of livestock distribution are normalized by area. Panels (a) and (b) compare the distribution of livestock obtained from the model and from Nigerien administrative sources, respectively. The size and shape of geographical units (16 units) is determined by the level of aggregation of the data in the administrative sources. Panels (c) and (d) compare the distribution of livestock obtained from the model and the distribution of cattle according to Lunde and Lindtjørn (2013) based on 1963 data. The geographical units (119 units) match those used for the reduced form analysis. Finally, panel (e) presents an index of transhumant pastoralism created by McGuirk and Nunn (2022) based on Murdock's *Ethnographic Atlas*. We recreated the index data ourselves using the map in their study.

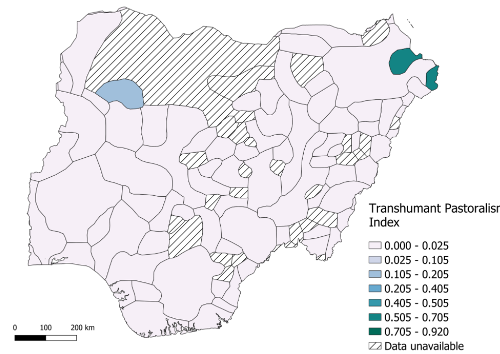
Figure E.11: Validation of the Model: Livestock Distribution in Nigeria c. 1963



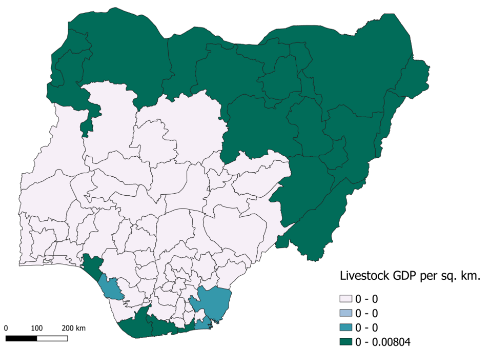
(a) Livestock per sq km (model)



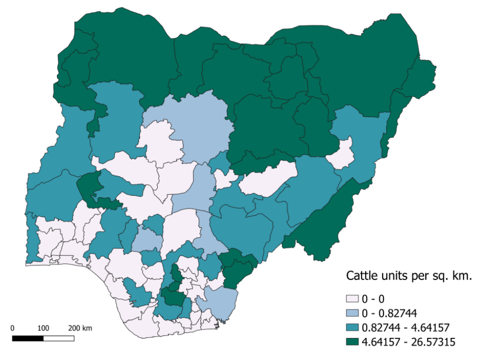
(b) Livestock per sq km (admin data)



(e) Transhumant pastoralism



(c) Livestock per sq km (model)



(d) Cattle per sq km (LL 2013)

Notes: These figures show for Nigeria circa 1963 how the spatial distribution of livestock predicted by the model compares to the spatial distribution obtained from alternative sources. All measures of livestock distribution are normalized by area. Panels (a) and (b) compare the distribution of livestock obtained from the model and from Nigerian administrative sources, respectively. The size and shape of geographical units (10 units) is determined by the level of aggregation of the data in the administrative sources. Panels (c) and (d) compare the distribution of livestock obtained from the model and the distribution of cattle according to Lunde and Lindtjørn (2013) based on 1963 data. The geographical units (83 units) match those used for the reduced form analysis. Finally, panel (e) presents an index of transhumant pastoralism as elaborated by McGuirk and Nunn (2022) based on Murdock's *Ethnographic Atlas*. We recreated the index data ourselves using the map in their study.

Table E.1: Reduced-Form Effect, Total Population, Niger 1950s-2010s

Dependent Variable:	Log Subdistrict Population in Year t				
Test:	Baseline	Full Lake Centroid	Other Inflow River Control	Climate Controls	Conley SE 250 Km
(Relative to the Omitted Year = 1962)	(1)	(2)	(3)	(4)	(5)
Proximity to Lake (log)*c.1970 ($t = 1969$)	-0.23**	-0.29**	-0.13	-0.24**	-0.23**
	[0.09]	[0.14]	[0.12]	[0.10]	[0.09]
Proximity to Lake (log)*c.1990 ($t = 1988$)	-0.41***	-0.59***	-0.48**	-0.42***	-0.41***
	[0.11]	[0.17]	[0.21]	[0.12]	[0.08]
Proximity to Lake (log)*c.2010 ($t = 2001$)	-0.31**	-0.48**	-0.48†	-0.32**	-0.31**
	[0.16]	[0.24]	[0.31]	[0.16]	[0.16]
Proximity to Lake (log)*c.2010 ($t = 2012$)	-0.33*	-0.52*	-0.38	-0.32*	-0.33**
	[0.19]	[0.29]	[0.37]	[0.19]	[0.16]
Subdistrict (119) FE, Year (17) FE	Y	Y	Y	Y	Y
District (31) Trends, Controls	Y	Y	Y	Y	Y

Notes: 119 subdist. x 17 years (1951-2017) = 2,023 obs. *Proximity to Lake* is the negative of the log Euclidean dist. to the lake centroid. We report the coefficients for the closest years to the year 1970, 1990 and 2010. Except in (2), we use the centroid of Lake Chad within Niger's territory (Appx Fig. E.4). (2): Centroid of the full lake. (3): We add a dummy if the subdistrict contains the Komadugu-Yobe river, interacted with year FE. (4): We also control for mean temperature and the log of mean annual rainfall in [t-2; t]. Controls (interacted with year FE): log Euclidean dist. to the largest/capital city and its square, and latitude. Conley SE 100 Km ((5): 250 km).

Table E.2: Effect of Proximity to the Lake, Total Population, Cameroon 1960s-2010s

Dependent Variable:	Log Subdistrict Population in Year t			
Test:	Baseline	Full Lake Centroid	Climate Controls	Conley SE 250 Km
(Relative to the Omitted Year = 1963)	(1)	(2)	(3)	(4)
Proximity to Lake (log)*c.1970 ($t = 1967$)	-0.19**	-0.36***	-0.19**	-0.19*
	[0.08]	[0.13]	[0.07]	[0.10]
Proximity to Lake (log)*c.1990 ($t = 1987$)	-0.40***	-0.80***	-0.48***	-0.40**
	[0.14]	[0.27]	[0.15]	[0.18]
Proximity to Lake (log)*c.2010 ($t = 2005$)	-0.36**	-0.72**	-0.34**	-0.36**
	[0.16]	[0.34]	[0.17]	[0.17]
Subdistrict (113) FE, Year (5) FE	Y	Y	Y	Y
District (47) Trends, Controls	Y	Y	Y	Y

*Notes:*113 subdist. x 5 yrs (1963-2005) = 563 obs. For each subdistrict centroid, *Proximity to Lake (log)* is the negative of the log Euclidean dist. to the selected lake centroid. We only report the coefficients for the closest years to the years 1970, 1990 and 2010. Except in col. (2), the lake centroid that we use is the centroid of Lake Chad within Cameroon's territory (Appx. Fig. E.4). (2): We use the centroid of the full lake. (3): We control for mean temperature and log mean annual rainfall in the period [t-2; t]. In addition to the district-specific linear trends, we include the following time-invariant controls interacted with year FE: log Euclidean distances to the largest city (Douala) and capital city (Yaoundé) and their square, latitude, a dummy if the subdistrict contains a major of the Chari-Logone river system, and a dummy if it contains a minor river of the river system. Conley SE 100 Km ((4): 250 km).

Table E.3: Effect of Proximity to the Lake, Total Population, Nigeria 1950s-2010s

Dependent Variable:	Log Subdistrict Population in Year t				
Test:	Baseline	Full Lake Centroid	Other Inflow River Control	Climate Controls	Conley SE 250 Km
(Relative to the Omitted Year = 1963)	(1)	(2)	(3)	(4)	(5)
Proximity to Lake (log)*c.1990 ($t = 1991$)	-0.47***	-0.54***	-0.46***	-0.52***	-0.47***
	[0.16]	[0.18]	[0.17]	[0.18]	[0.11]
Proximity to Lake (log)*c.2010 ($t = 2006$)	-0.37*	-0.42*	-0.49**	-0.38*	-0.37***
	[0.19]	[0.22]	[0.21]	[0.20]	[0.12]
Subdistrict (83) FE, Year (4) FE	Y	Y	Y	Y	Y
District (24) Trends, Controls	Y	Y	Y	Y	Y

Notes: 83 subdist. x 4 years (1952-2006) = 332 obs. For each subdistrict centroid, *Proximity to Lake (log)* is the negative of the log Euclidean dist. to the selected lake centroid. We only report the coefficients for the closest years to the years 1990 and 2010. Except in (2), the lake centroid that we use is the centroid of Lake Chad within Nigeria's territory (Appx. Fig. E.4). (2): We use the centroid of the full lake. (3): We add a dummy if the subdistrict contains the Komadugu-Yobe river, interacted with year FE. (4): We control for mean temperature and the log of mean annual rainfall in the period [t-2; t]. In addition to the district-specific linear trends, we include the following time-invariant controls interacted with year FE: log Euclidean distances to the largest city (Lagos), the capital city (Abuja), the capital city of the North (Kano), the informal capital cities of the oil-producing Delta region (Port Harcourt and Benin City), and their square, a dummy if the subdistrict contained oil reserves c. 1960, latitude, a dummy if the subdistrict contains a major of the Chari-Logone river system, and a dummy if the subdistrict contains a minor river of the river system. Conley SE 100 Km ((5): 250 km).

Table E.4: Effect of Proximity to the Lake, Total Population, Chad 1940s-2010s

Dependent Variable:	Log Subdistrict Population in Year t				
Lake Centroid:	Baseline	Chad	Chad	Chad North vs. South	
	Chad North	Full	South	Chad North	Chad South
(Relative to the Omitted Year = 1965)	(1)	(2)	(3)	(4)	
Proximity to Lake (log)*c.1990 ($t = 1993$)	-0.54***	-0.33**	-0.18**	-0.71**	0.19
	[0.08]	[0.15]	[0.08]	[0.31]	[0.231]
Proximity to Lake (log)*c.2010 ($t = 2009$)	-0.62***	-0.48***	-0.38***	-0.47***	-0.29
	[0.17]	[0.16]	[0.10]	[0.13]	[0.206]
Subdistrict (138) FE, Year (5) FE	Y	Y	Y	Y	
District (36) Trends, Controls	Y	Y	Y	Y	
Test:	Chad North vs. Fitri		Outflow	Climate	Conley
	Chad North	Chad Fitri	Control	Controls	250 Km
(Relative to the Omitted Year = 1965)	(5)		(6)	(7)	(8)
Proximity to Lake (log)*c.1990 ($t = 1993$)	-0.48***	0.17	-0.50***	-0.53***	-0.54***
	[0.10]	[0.12]	[0.08]	[0.10]	[0.06]
Proximity to Lake (log)*c.2010 ($t = 2009$)	-0.57***	0.16	-0.54***	-0.63***	-0.62***
	[0.17]	[0.14]	[0.15]	[0.16]	[0.13]
Subdistrict (138) FE, Year (5) FE	Y		Y	Y	Y
District (36) Trends, Controls	Y		Y	Y	Y

Notes: 138 subdist. x 5 years (1948-2009) = 690 obs. For each subdistrict centroid, *Proximity to Lake (log)* is the negative of the log Euclidean distance to the selected lake centroid. We only report the estimated coefficients for the closest years to the year 1990 and the year 2010. In col. (1), the lake centroid that we use is the centroid of the Northern section of the lake that belongs to Chad's territory (see Fig. E.4 for details). In col. (2), we use the centroid of the full lake area within Chad's territory (Ibid.). In col. (3), we use the centroid of the Southern section of the lake that belongs to Chad's territory. In col. (4), we use both the Northern and Southern centroids. In col. (5), we also consider the centroid of Lake Fitri which is fully contained within Chad's territory (see Fig. 4 for the location of Lake Fitri in Chad). In col. (6), we add a dummy if the subdistrict contains the Bahr el-Ghazal – a dry riverbed that was before the 1940s an outflow river of Lake Chad – which we interact with year FE. Col. (7): We control for mean temperature and the log of mean annual rainfall in the period [t-2; t]. In addition to the district-specific linear trends, we include the following time-invariant controls which we interact with year FE: log Euclidean distance to the largest/capital city (N'Djamena) and its square, latitude, a dummy if the subdistrict contains a major of the Chari-Logone river system, and a dummy if the subdistrict contains a minor river of the Chari-Logone river system. Conley SEs 100 Km (except in col. (8) where we use 250).

Table E.5: Robustness to Excluding Controls

Dependent Variable:	Log Subdistrict Population in Year t						
(Relative to the Omitted Year)	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Columns (1)-(4): Cameroon				(5)-(7): Chad		
Excluding:	Baseline	Rivers	Largest	City	Baseline	Rivers	Larg/City
Proximity to Lake (log)*c.1990	-0.40***	-0.35**	-0.39***	-0.29***	-0.54***	-0.56***	-0.26**
	[0.14]	[0.17]	[0.14]	[0.11]	[0.08]	[0.13]	[0.11]
Proximity to Lake (log)*c.2010	-0.36**	-0.34**	-0.34**	-0.21*	-0.62***	-0.66***	-0.56***
	[0.16]	[0.16]	[0.15]	[0.11]	[0.17]	[0.17]	[0.15]
	(1)-(2): Niger		Columns (3)-(7): Nigeria				
Excluding:	Baseline	Larg/City	Baseline	Rivers	Largest	City	Oil
Proximity to Lake (log)*c.1990	-0.41***	-0.17†	-0.47***	-0.46***	-0.40**	-0.21	-0.63***
	[0.11]	[0.10]	[0.16]	[0.16]	[0.19]	[0.25]	[0.18]
Proximity to Lake (log)*c.2010	-0.31**	-0.19	-0.37*	-0.39**	-0.46†	-0.16	-0.75***
	[0.16]	[0.17]	[0.19]	[0.20]	[0.28]	[0.36]	[0.22]

Notes: This table shows the long-run effects (estimated relative to the omitted pre-1963 year) when excluding controls: (A) *Rivers:* Two dummies for being crossed by a major river or a minor river of the Logone-Chari river system, interacted with year dummies. This only concerns Cameroon, Chad and Nigeria (Niger does not have such rivers in its territory); (B) *Largest:* The logged Euclidean distance to the largest city, and its square, and their interactions with year dummies; (C) *City* or *Larg/City:* All the city controls, i.e., the logged Euclidean distances to the largest city and the capital city, their square, and their interactions with year dummies. This controls for spatial development patterns related to economic or political centralization (or decentralization). Additionally removing the capital city controls only concerns Cameroon and Nigeria, as the largest city is not the capital city in Cameroon (Douala vs. Yaoundé) and Nigeria (Lagos vs. Abuja); and (D) *Oil:* The oil controls interacted with year dummies (this only concerns oil-producing Nigeria): (Di) a dummy if there were oil deposits in c. 1960; (Dii) the logged Euclidean distances to Port Harcourt and Benin City, the informal capital cities of the oil-producing Delta region, and their squares; and (Diii) the logged Euclidean distance to Kano, the North's capital, and its square. A large share of oil revenues is indeed shared with the Delta and Northern regions (Kano, Benin City and Port Harcourt are the 2nd, 4th and 5th largest city today, respectively). Conley SEs (100 km). *** p<0.01, ** p<0.05, * p<0.1, † p<0.15.

Table E.6: Long-Term Reduced-Form Effect, Rural Population, Distance Bins

Dependent Variable:	Log Subdistrict Population in t			Log Subdistrict Population in t		
Omitted Year = Early 60s	Total	Rural (5K)	Rural (20K)	Total	Rural (5K)	Rural (20K)
	Niger (t = 2001)			Niger (t = 2012)		
0-150 Km*ca.2010 (t)	-0.26**	-0.45***	-0.51***	-0.34**	-0.69***	-0.76***
	[0.12]	[0.11]	[0.10]	[0.14]	[0.12]	[0.13]
150-300 Km*ca.2010 (t)	-0.26**	-0.48***	-0.35***	-0.10	-0.46***	-0.43***
	[0.11]	[0.12]	[0.09]	[0.15]	[0.14]	[0.14]
300-450 Km*ca.2010 (t)	-0.13	-0.17*	-0.23***	-0.02	-0.18*	-0.28***
	[0.16]	[0.10]	[0.09]	[0.18]	[0.10]	[0.08]
	Cameroon (t = 2005)			Chad (t = 2009)		
0-150 Km*ca.2010 (t)	-1.41***	-0.90***	-1.90***	-1.03***	-0.50*	-0.48†
	[0.27]	[0.20]	[0.40]	(0.29)	(0.27)	(0.32)
150-300 Km*ca.2010 (t)	-0.98***	-1.11***	-2.08***	-0.96***	-0.53**	-0.48*
	[0.09]	[0.11]	[0.25]	(0.25)	(0.22)	(0.27)
300-450 Km*ca.2010 (t)	-1.08***	-1.10***	-2.29***	0.01	-0.51***	-0.50***
	[0.06]	[0.11]	[0.23]	(0.03)	(0.11)	(0.15)
Subdistrict FE, Year FE	Y	Y	Y	Y	Y	Y
District Trends, Controls	Y	Y	Y	Y	Y	Y

Notes: Obs.: Niger (1951-2012): 119 subdist. x 12 yrs = 1,428. Cameroon (1963-2005): 113 subdist. x 5 yrs = 565. Chad (1948-2009): 138 subdist. x 5 yrs = 690. We omit 1962, 1963 and 1965, respectively. Rural pop. 5K (20K) = pop. - pop. of 5K+ (20K+) cities. Conley SE 100 Km

Table E.7: Proximity to Lake Chad and Conflict, Poisson Model, Robustness

Dependent Variable:	Number of Conflict Events in 1997-2008, Poisson Model					
Lake 0-150 Km	2.84***	3.60***	2.46***	-0.60	-0.32	-0.62
	(0.69)	(0.86)	(0.72)	(0.80)	(0.91)	(0.81)
Lake 150-300 Km	2.22***	2.81***	1.97***	-0.65**	-0.24	-0.64*
	(0.66)	(0.75)	(0.64)	(0.34)	(0.33)	(0.34)
Lake 300-450 Km	0.22	0.93	-0.17	-1.59***	-1.36***	-1.61***
	(0.57)	(0.68)	(0.61)	(0.31)	(0.32)	(0.30)
Mean	1.30	0.62	0.68	5.10	2.85	2.09
Observations	453	453	453	453	453	453
# Non-Zeros	83	57	72	163	133	124
Country FE	Y	Y	Y	Y	Y	Y
Controls (See Table Notes)	Y	Y	Y	Y	Y	Y

Notes: This table shows the cross-sectional correlation between proximity to Lake Chad and the number of conflict events when using a Poisson model to account for a large number of zeros among the 453 subdistricts. Non-organized violence includes "protests" and "riots". Organized violence includes "battle" and "violence against civilians" as well as "explosions/remote violence" and "strategic developments", which are rarer events (effects not shown). Controls: log area and log pop. c. 1990, log Euclidean distances to the largest city and the capital city, and their squares, and latitude. Conley SE 100 km *** p<0.01 ** p<0.05 * p<0.1

Table E.8: Expenditure Shares for Each Country, Circa 1963 and Circa 2010

Circa 1963	Cameroon	Chad	Niger	Nigeria	Pop-Wtd Avg	Final
Year:	1961-65	1960-65	1960-65	1955-65	1955-1965	Selection
Agriculture	0.32	0.49	0.50	0.32	0.34	0.35
Livestock	0.13	0.14	0.15	0.13	0.13	0.10
Fishing	0.12	0.10	0.09	0.12	0.12	0.10
Urban	0.30	0.16	0.18	0.33	0.31	0.35
Housing	0.13	0.11	0.08	0.10	0.10	0.10
Circa 2010	Cameroon	Chad	Niger	Nigeria	Pop-Wtd Avg	Final
Year:	2007	2003	2007	2009	2003-2009	Selection
Agriculture	0.31	0.56	0.49	0.45	0.45	0.45
Livestock	0.06	0.09	0.05	0.06	0.06	0.05
Fishing	0.04	0.03	0.00	0.05	0.05	0.05
Urban	0.54	0.27	0.38	0.31	0.33	0.35
Housing	0.05	0.05	0.08	0.13	0.11	0.10

Notes: This table reports expenditure shares c. 1963 before the shrinkage of the lake as well as c. 2010. The "Final Selection" column shows the expenditure shares used in our analysis. See Appx. Section E for details on the sources.

Table E.9: Selected Factor Intensity Shares

Sector	Labor share	Land share	Water share
Agriculture	0.40	0.60	0.00
Livestock	0.30	0.70	0.00
Fishing	0.30	0.00	0.70
Urban sector	0.80	0.20	0.00

Notes: See the main text for details on the sources.

Table E.10: Main Selected Elasticities

Parameter	Value	Source(s)
Trade Elasticity, Primary Sectors	4 ($\sigma = 5$)	Simonovska and Waugh (2014), Donaldson (2018)
Trade Elasticity, Urban Sector	1 ($\sigma = 2$)	Boehm et al. (2020)
Migration Elasticity (η)	3.0	Various sources (see text foe details)
Agglomeration Externality (γ)	0.1	Combes and Gobillon (2015); Ahlfeldt and Pietrostefani (2019)
Congestion Force (λ)	0.32	Desmet et al. (2018)

Table E.11: Assumed Road and Boat Speeds (kph = km per hour)

Category	Speed (kph)	Source
Highway / motorway	80	Jedwab and Storeygard (2021)
Paved road	60	Jedwab and Storeygard (2021)
Improved road (gravel / laterite)	40	Jedwab and Storeygard (2021)
Dirt road / track	12	Jedwab and Storeygard (2021)
Lake (travel by boat)	10	See table notes
No road / no lake / path	3	Assumed

Notes: This table reports the speeds used to calculate travel times (hours) across subdistricts. The road-based values come from Jedwab and Storeygard (2021). For boat travel on the lake, we assume a speed of 10 kph. Historically, canoes would travel at a speed of 5 kph in West Africa (Smith, 1970; Manning, 1985). But "in the 1950s motorized pirogues were introduced to the area" and most trips in the remaining water areas now take place with motorized pirogues (Magrin and de Montclos, 2018, pp. 64 and 169). These motorized pirogues have an average speed of 20 kph. We thus assume an average (historical) speed of 10 kph for boat travel.

Table E.12: Estimation of Trade Costs, Cameroon and Niger, c. 1963

	(1) OLS	(2) IV	(3) OLS	(4) IV
	Dependent Variable: Log of the Price in Location j ($\ln p_{oj}$)			
Panel A:	*"Cost of Imported Goods" for 48 Cameroonian Cities, 1965*			
Travel time (t_{oj}; hours)	0.089***	0.090***	0.088***	0.090***
	(0.005)	(0.004)	(0.005)	(0.003)
Log City Pop. $_{j,c.\ 1965}$			-0.027***	-0.027***
			(0.007)	(0.007)
Observations	48	48	48	48
R-squared	0.815	0.815	0.851	0.850
IV F-statistic		487.7		488.3
Panel B:	*Price of Imported Petroleum Products in 19 Nigerien Cities, 1962*			
Travel time (t_{oj}; hours)	0.061***	0.058***	0.064***	0.061***
	(0.007)	(0.008)	(0.007)	(0.007)
Log City Pop. $_{j,c.\ 1962}$			0.012	0.011
			(0.009)	(0.008)
Observations	228	228	228	228
R-squared	0.899	0.898	0.909	0.908
IV F-statistic		228.5		234.5
Product-Trimester FE	Y	Y	Y	Y

Notes: This table reports the results used to estimate the parameter that transforms road-based travel times (hours) into iceberg trade costs (see main text and below for details). Panel A reports the results for Cameroon. We use data on the *cost of imported goods* for 48 Cameroonian cities in 1965. Source: Orstom (1965). *Atlas du Cameroon, Planche XVII. Les villes et leurs fonctions.* Orstom. The "imported goods" are described as originating from Douala, Cameroon's only international port. However, one caveat is that we do not know how the basket of imported goods varies across cities, i.e. how homogenous our price data is. Panel B reports the results for Niger. We use data on the *price of petroleum products* for 19 Nigerien cities in 1962. More precisely, we know the price of gasoline, oil and diesel fuel in each trimester of 1962. Source: Republique du Niger (1962). *Annuaire Statistique.* Commissariat General au Plan. As a result, we have 3 x 4 x 19 = 228 observations. In this case, gasoline / oil / diesel is reported to originate from the border town of Gaya, close to both Benin and Nigeria. Panels A and B: For each country, we estimate the following regression: $\ln p_{ojs} = \alpha_s + \delta t_{oj} + \gamma \ln pop_j + \epsilon_{ojs}$, where o is the origin location, t_{oj} is the road-based travel time (hours) between origin o and destination j, and ϵ_{ojs} is the error term (s is the sector). In some specifications, we also control for the population of city j c. 1963 as market size could also influence prices locally (whether due to demand or supply factors). Given potential endogeneity concerns regarding the "placement" of transportation networks, we also instrument travel times with the Euclidean distance between the origin and destination locations (assuming it does not impact prices through another channel than travel costs). For Niger, since we consider 3 petroleum products x 4 trimesters, we include 12 product-trimester fixed effects. Lastly, we consider Conley standard errors (100 km). With the best specification (2SLS + population control; see column (4)), δ equals = 0.090*** in Cameroon and 0.061*** in Niger. Using as weights the population of each country in 1965, we find an average value of about 0.08.

Table E.13: Fundamental Amenities & Educational and Health Infrastructure c. 1963

Panel A: Cameroon (arrondissements)	Dependent Variable: Log of the Fundamental Amenity Value			
adjusted R2	0.82	0.84	0.77	0.82
log index	Y	Y	N	N
log index squared	N	Y	N	N
log components	N	N	Y	Y
log components squared	N	N	N	Y
no. variables; no. obs	2; 85	4; 85	8; 85	16; 85
Panel B: Chad (prefectures)	Dependent Variable: Log of the Fundamental Amenity Value			
adjusted R2	0.68	0.59	0.55	0.58
log index	Y	Y	N	N
log index squared	N	Y	N	N
log education components	N	N	Y	N
log health components	N	N	N	Y
no. variables; no. obs	2; 14	4; 14	10; 14	6; 14
Panel C: Niger (subdivisions)	Dependent Variable: Log of the Fundamental Amenity Value			
adjusted R2	0.73	0.75	0.79	0.91
log index	Y	Y	N	N
log index squared	N	Y	N	N
log components	N	N	Y	Y
log components squared	N	N	N	Y
no. variables; no. obs	2; 24	4; 24	8; 24	16; 24
Panel D: Nigeria (provinces; regions)	Dependent Variable: Log of the Fundamental Amenity Value			
adjusted R2	0.76	0.75	0.43	0.43
log education index	N	N	Y	Y
log education index squared	N	N	N	Y
log health index	Y	N	N	N
log health index squared	N	Y	N	N
no. variables; no. obs	1; 29	2; 29	1; 10	2; 10

Notes: **Cameroon:** Health index = 11*public hospitals + 15.7*private hospitals + 7.9*departmental centers of preventive medicine + 3*private dispensaries + 1*public dispensaries. Education index = 11.8*high schools + 3*secondary schools + 1*primary schools. Components: We use the values above divided by population c. 1963 as well as the values above divided by area. **Chad:** Health index = 22*hospitals + 11*medical centers + 7.3*epidemics control centers + 2.9*infirmaries + 1*dispensaries. Education index = 41.1*high schools + 30.8*secondary schools + 1*primary schools. Components: We use the values above divided by population c. 1963 as well as the values above divided by area. We first use the education variables only, then the health variables only. **Niger:** Health index = 43.5*hospitals + 14.5*health centers + 4.8*small hospitals + 5.1*nurseries + 1*dispensaries. Education index = 360*high schools + 45*secondary schools + 1*primary schools. Components: We use the values above divided by population c. 1963 as well as the values above divided by area. **Nigeria:** Health index = 16.3*federal general hospitals + 8.2*federal special hospitals + 8.2*federal infectious diseases hospitals + 2.1*federal maternity centres + 1*dispensaries + 16.3*0.9*federal regional/local general hospitals and nursing homes +8.2*regional/local special hospitals + 8.2*regional/local infectious diseases hospitals + 2.1*regional/local maternity centres and rural health centres + 1*regional/local dispensaries. Education index = 2790*universities + 12.3*secondary schools + 1*primary schools. We only use the indexes for Nigeria. See Appx. Section F2. for details.